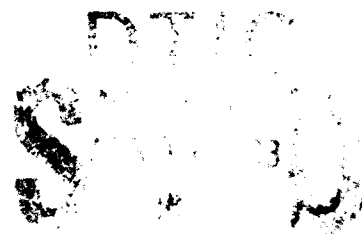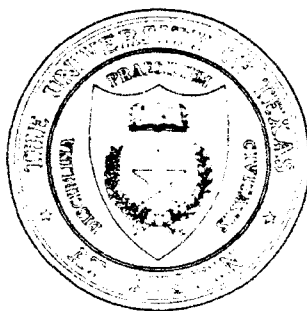AD-A262 733

ANNUAL REPORT ON ELECTRONICS RESEARCH

AT THE UNIVERSITY OF TEXAS AT AUSTIN

NO. 46

For the period May 15, 1992 through February 14, 1993

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract AFOSR F49620-92-C-0027

February 14, 1993

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Submitted by Edward J. Powers

on behalf of the Faculty and Staff

of the Electronics Research Center

February 14, 1993

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712-1084

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DIRECTOR'S OVERVIEW

and

SIGNIFICANT ACCOMPLISHMENTS

DIRECTOR'S OVERVIEW

This report covers the nine-month period May 15, 1992 to February 14, 1993 and reports on work carried out under research contract AFOSR F49620-92-C-0027. The current JSEP program at The University of Texas at Austin is a relatively balanced program with five solid-state, two electromagnetic and two information electronics research units. Our work in solid-state electronics brings together the diverse talents of researchers in both physics and electrical engineering to attack problems in the design, realization and analysis of high-speed and optoelectronic devices. To this end research is being carried out in growth of multilayer heterostructures by molecular beam epitaxy, control of spontaneous emission in microcavity semiconductor lasers, microcavity photodetectors, charge transport through and across heterobarriers, and femtosecond physics of electronic materials and devices. The overall thrust of the two electromagnetic units is the application of electromagnetic theory to highly practical situations involving the use of new solid state devices and fabrication processes in guided wave rf circuits, and electromagnetic scattering from gaps, cracks, joints and cavities. The theme of our information electronics program involves the utilization of innovative signal processing concepts to extract information from signals that would otherwise be unavailable. Specific work involves the development of various methodologies for the analysis and interpretation of multisensory signals, and the utilization of higher-order statistical signal processing to analyze and interpret random data from nonlinear systems and to model such systems and associated nonlinear phenomena.

In the following pages we report on a significant accomplishment carried out under the direction of Professor Dean Neikirk. This accomplishment involves epitaxial liftoff of GaAs/AlGaAs thin film device structures for hybrid integration on silicon and quartz substrates

Finally we mention that the new $25 million building to house microelectronics and material sciences research at U.T.'s Balcones Research Center is completed and the involved faculty have relocated their offices and laboratories to this new location. Several JSEP faculty are involved in the new NSF Science and Technology Center. Lastly, JSEP Faculty were very successful in winning awards in the most recent Texas Advanced Technology/Research Program. All of these activities have had and will continue to have a positive synergistic impact on The University of Texas at Austin JSEP program.

Edward J. Powers for the
U.T. JSEP faculty participants

Epitaxial Liftoff of GaAs/AlGaAs Thin Film Device Structures for Hybrid Integration on Silicon and Quartz Substrates

Professor Dean P. Neikirk (512) 471-4669

With the advent of the epitaxial liftoff (ELO) technique, extremely thin (100Å) single crystal films of GaAs or low Al mole fraction (x < 0.4) AlGaAs grown by MBE or MOCVD can be removed from their GaAs substrates. This technique utilizes a thin AlAs layer between the films of interest and the GaAs substrate. The high etch selectivity of AlAs over GaAs or low Al mole fraction AlGaAs in 10% hydrofluoric acid is used to completely undercut the films of interest, thus separating them from the GaAs substrate. A wide variety of pre-fabricated device structures whose epilayers were grown on AlAs release layers can also be separated from their substrates using the ELO technique. Through the use of Apiezon W "black" wax as a carrier for these extremely thin films, the selective etching of these films can be facilitated as well as allowing these thin epitaxial films to be easily manipulated and bonded to alternative substrates without any damage. One of the optimal alternative substrates is silicon which provides the opportunity to integrate III-V devices with silicon devices. Furthermore, the surrogate silicon substrate acts as a better heat sink for GaAs/AlGaAs devices with high power dissipation since silicon has a higher thermal conductivity than GaAs substrates. For many applications, the ELO method provides an alternative to the conventional GaAs on Si technologies. Quartz substrates also offer special advantages since they are transparent and have a lower dielectric constant than the GaAs substrate. The combination of these techniques and devices using "hybrid microelectronics" should allow the fabrication of new circuits with a higher degree of optimization.

We have been able to apply the ELO technique to a variety of GaAs/AlGaAs MBE grown device structures. The surface area of our ELO films are approximately 1 cm^2 with our largest area films on the order of 4 cm^2. The thicknesses of our ELO films varied with device structure and were on the order of 5000 Å to 2 µm. We applied the ELO technique on quantum well devices such as AlAs/GaAs and strained-layer InGaAs/AlAs high current density double barrier resonant tunneling diodes (DBRTDs). These devices have been bonded to both Si and quartz substrates using palladium, indium, and conductive silver epoxies. By bonding the substrate-less DBRTD structures on alternative substrates such as Si or even substrates of higher thermal conductivity, we have observed that valley currents decrease, PVCRs increase, and the devices can be biased at significantly higher voltages before breaking down. Another device structure that has shown significant gains as a result of ELO is a microwave transmission line which is composed of a Schottky-contacted coplanar waveguide (CPW) on a thin epitaxially grown, lightly doped GaAs film. This device exhibits maximum sensitivity to optical illumination at high reverse bias where the GaAs epi-film is almost fully depleted. By lifting this pre-fabricated device from its S.I. GaAs substrate and bonding it to transparent quartz, we were able to dramatically increase its optical sensitivity and lower the dielectric loss. As a result, greater phase shifts and lower insertion losses were observed. In a similar manner, ELO double heterostructure LED structures have been bonded to quartz for purposes of backside emission through the quartz substrate.

We are currently one of only three main groups in the US pursuing ELO-fabricated devices, the other two being from Bellcore and Georgia Tech. More recently, work on the application of ELO to heterojunction bipolar transistors has also been performed at Wright-Patterson AFB (Solid State Electronics Directorate, Wright Laboratory). In addition, we have very recently transferred our epitaxial lift-off technique to H. B. Dietrich's group at the Naval Research Laboratory (Microwave Technology Branch, High Frequency Devices and Materials Section). They have used our technique to prepare substrate-less superlattice devices for optical applications. We have also grown MBE superlattice layers for their use in this device.

Hybrid versus monolithic assembly of high frequency circuits

Hybrid assembly of discretely packaged devices

- individual active devices can be optimized
- large area passive distributed circuitry produced on low cost substrates
- packaging parasitics kill performance
- cost of assembly prohibitive

Conventional monolithic integration (MIMICs)

- substrate effects can dominate behavior of microwave and millimeterwave circuits
  - dielectric loss for microstrip
  - surface wave losses for antennas, coplanar waveguide
- epitaxial growth substrates offer very limited choices
- simultaneous optimization of all devices may be very difficult

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Motivation for Hybrid Integration

The use of hybrids typically allows the use of the device and its material system that is best suited for each function.

- Integration of electronic, optical, and microwave devices

Monolithic integration is useful for high densities of similar devices, but restricts the integration of dissimilar devices to one material system.

Monolithic integration for high frequency (MIMIC)

- Substrate effects can dominate behavior of microwave and millimeterwave circuits
  - Dielectric loss for microstrips
  - Surface wave losses for antennas, coplanar waveguides

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"Hybrid" / monolithic fabrication

Use ELO processes to create "hybrid substrates"

- use large area, low loss, low cost substrates for passive rf circuits
- active layers bonded to local regions
- epilayers for each device grown separately
  - growth sequences individually optimized

IC-like planar processing still applicable

- small feature delineation performed prior to lift-off
- large feature patterns produced before and / or after bonding
  - little or no "packaging" parasitics

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Hybrid "Back-to-back" Bonding of ELO CPW Phase Shifters and ELO Light Emitting Diodes
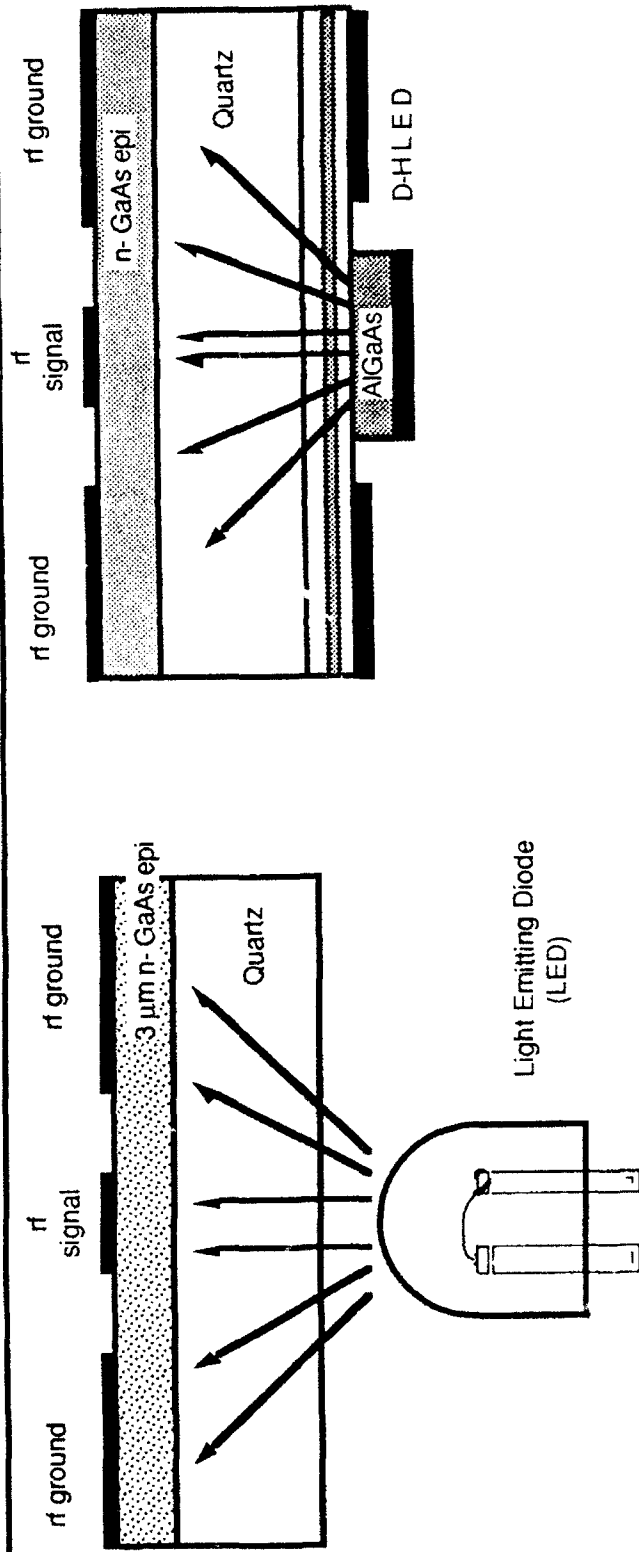
After Epitaxial Liftoff (ELO):

- High dielectric constant substrate removed
- Illumination from back avoids electrode shadowing

At 30 GHz:

- Illumination from top: phase shift = 45° insertion loss = -15 dB.
- After ELO, top: phase shift = 250° insertion loss = -25 dB.
- After ELO, back: phase shift = 350° insertion loss = -40 dB

Neikirk, Univ. of Texas, November 12, 1992

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I. SOLID STATE ELECTRONICS

Research Unit SSE92-1   Growth of Multilayer Heterostructures by Molecular Beam Epitaxy

Principal Investigator: Professor Ben G. Streetman (512) 471-1754

Graduate Students: C. Hansing, T. Rogers, K. Sadra, A. Srinivasan

A. SCIENTIFIC OBJECTIVES: Our objective is to study the MBE growth of multilayer heterostructures in GaAs, AlGaAs, InGaAs, and related compounds, to improve the quality and variety of structures available and to apply these structures to electronic and optoelectronic devices. The research is designed to understand and improve heterostructures requiring monolayer control, precise alloy composition and doping, regrowth after lithographic processing, and other advanced MBE growth techniques. The resulting structures are applied in novel devices, in collaboration with other faculty at UT-Austin including other JSEP units. We believe that research on advanced crystal growth coupled with daily involvement with device applications is the most productive mode for carrying out this research. Therefore, the major goals of this work are to develop new understanding of MBE growth, apply that understanding to the growth of high-quality multilayer heterostructures, characterize those structures, and work with related JSEP units to advance the science and art of devices based on such multilayers.

B. PROGRESS: Our research during the past year has been concentrated primarily in four areas: studies of δ-doped quantum wells and the influence of As overpressure on dopant incorporation; studies of growth dynamics including effects of growth interruption on crystal quality; examination of carrier transport and surface effects in MBE-grown layers; and applications of low-temperature grown layers as semi-insulating regions and growth of Bragg reflectors for vertical cavity surface-emitting laser structures and microcavity detectors.

Continuing our previous work on δ-doping and modulation doping of quantum wells (3, 7), we have studied the effects of changing As_4/As_2 flux ratio from our As cracking source on Si and Be δ-doped GaAs grown by MBE. We found that the carrier concentration increases as the As_4/As_2 flux ratio increases. The spatial confinement of carriers in the induced potential well is also enhanced using high As_4/As_2 flux ratio. These effects are attributed to the enhancement of dopant incorporation by As_4 during the δ-doping growth period. We have recently extended this study using a new real-time flux monitoring system for control of our valved arsenic source (19,20).

We have studied the influence of growth conditions on RHEED dampening and quantum well photoluminescence. By varying the growth temperature and As/Ga ratio, we found a clear correlation as both the RHEED dampening and the PL linewidths were found to increase with an increasing As/Ga ratio (22). These studies build on earlier work we have done relating RHEED and PL to AsO contamination (1), growth interruption (11), and growth of quantum wells on low-temperature grown buffer layers (12). Recently, in collaboration with Wright-Patterson AFB, we have applied in-situ ellipsometry to study the As capping of GaAs surfaces and the subsequent removal of the As cap (29). We observe changes in the ellipsometric response in a temperature window between 300°C and 100°C, with a signature change in the response at 250°C. We found that this signature could be used to assist in accurately controlling

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the growth conditions of LT GaAs layers. We have applied this technique to the study of critical thickness, relating the ellipsometric response to the formation of submicron polycrystalline regions, as shown by low angle thin film x-ray diffractometry. This technique appears promising for studying semi-insulating layers grown at reduced temperatures.

In our continuing studies of carrier transport and applications to multilayer heterostructures, we have done extensive calculations of the coupled hole-phonon system and minority-electron transport in p-GaAs (16). Using Monte-Carlo calculations including dynamic screening and plasmon-phonon coupling, we have calculated velocity-field characteristics of minority electrons in p^+-GaAs and find that calculated electron velocities are higher than expected. We are currently working on drift and diffusion in low-dimensional p-n junction structures (28) and calculated response of multiple p-i-n photodiodes (26). Another interesting area of basic semiconductor physics under study is a collaborative effort with Prof. Shih of the UT-Austin Physics department to employ the scanning tunneling microscope in studying multilayers grown by MBE (18). We have found that the STM is capable of resolving heterolayers and also studying differences in doping and materials. It appears that the contrast observed is primarily due to tip-induced band bending and the difference in work function between p and n-type regions.

The results of our materials studies and MBE growth research have allowed us to make substantial progress in electronic and optoelectronic device development. In addition to continuing studies of resonant tunneling structures in collaboration with Neikirk (EM92-1), we have made a number of advances in VCSEL development with Deppe (SSE92-2) and are continuing to work with Campbell on microcavity detectors (SSE92 3). Our work on VCSEL structures is particularly interesting(4, 6, 8, 9, 14, 15, 21, 23, 24) in that we have been able to incorporate a number of MBE growth techniques developed in this JSEP program into these devices. For example, we have developed techniques for incorporating LT-grown AlGaAs as semi-insulating lattice matched regions with selective etching and regrowth to provide current funneling in VCSEL devices(21). The background developed in this unit on growth of quantum wells and superlattices, pseudomorphic growth, regrowth on layers after photolithography and etching, and growth of semi-insulating GaAs and AlGaAs, has made these device applications possible. Further discussion of these devices is presented in SSE92-2 and 3.

C. FOLLOW-UP STATEMENT: We will continue to study the details of MBE growth, and the quality of layers in the InGaAlAs system using both *in-situ* techniques such as RHEED and ellipsometry, and *ex-situ* electrical and optical measurements. Devices employing multilayer heterostructures will be studied in collaboration with other units in this program and with other faculty in the Microelectronics Research Center. During the upcoming year we will concentrate on MBE growth techniques of use in VCSELs, microcavity detectors, and other structures for various optoelectronic applications.

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II. LIST OF CONFERENCE PROCEEDINGS (*JSEP supported in whole or in part)

*T.J. Mattord, D.P. Neikirk, A. Srinivasan, A. Tang, K. Sadra, T.R. Block, Y.C.Shih, and B.G. Streetman, "Real-time Flux Monitoring for Feedback Control of a Valved Arsenic Source," Proceedings of the North American Conference on Molecular Beam Epitaxy (Ottawa, 1992).

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III. LIST OF PRESENTATIONS (*JSEP supported in whole or in part)

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IV. LIST OF THESES AND DISSERTATIONS (*JSEP supported in whole or in part)

Master of Science

*Anand Srinivasan, May 1992, "Molecular Beam Epitaxy of Low Temperature Gallium Arsenide."

PhD

*T.J. Rogers, December 1992, "MBE Grown Microcavities for Optoelectronic Devices."

V. CONTRACTS AND GRANTS

Army Research Office, "Studies of MBE Growth for Electronics and Photonics," Ben Streetman, Principal Investigator.

NSF (STC) , "Center for Synthesis, Growth and Analysis of Electronic Materials," Mike White, Principal Investigator.

Texas Advanced Technology Program," Vertical Cavity Surface Emitting Lasers for Integrated Optoelectronic Applications," Ben Streetman and Dennis Deppe, Principal Investigators.

Texas Advanced Research Program, "Bipolar Low-dimensional Phenomena," Ben Streetman, Principal Investigator.

THE UNIVERSITY OF TEXAS AT AUSTIN   MICROELECTRONICS RESEARCH CENTER
                                         SOLID STATE ELECTRONICS

Research Unit SSE92-2:   Control of Spontaneous Emission in Microcavity
                         Semiconductor Lasers

Principal Investigator: Professor Dennis G. Deppe (512) 471-4960

Graduate Students: Diana L. Huffaker and Zhe Huang

A.   SCIENTIFIC OBJECTIVES: The scientific objective of this research is the investigation of the effect of an optical cavity on the spontaneous emission characteristics of a semiconductor, and how the control of the spontaneous emission may impact the characteristics of a microcavity laser. Since the realization of the semiconductor microcavity is achieved in the form of the so-called Vertical-Cavity Surface-Emitting (VCSEL), the project is also directed towards the fabrication of practical, low-threshold semiconductor lasers. Besides an improved understanding into the physics of light emission from semiconductors and dipole-mirror interactions, the goal of the project is the realization of ultra-low threshold semiconductor lasers.

The approach can be described as both a theoretical attack on the role of spontaneous emission in semiconductor lasers, and the development of the fabrication and characterization tools to implement the cavity structures which capitalize on the cavity effects. The theoretical investigation into the role of controlled spontaneous emission on laser performance is important, since a straightforward model of the longitudinal cavity's effect has not been presented, and is currently debated in the field of semiconductor lasers. While the role of lateral optical confinement in the laser threshold equations has been appreciated since nearly the time of the conception of the laser, early work did not take note that the emission characteristics of the dipoles themselves contained in the cavity depended in any critical way on ' e cavity. This lack of concern arose from the experimentally known fact that for a large ca ty (large with respect to the emission wavelength) a dipole contained in a cavity radiated as if in free space. Only recently with the experimental realization of wavelength dimensional optical cavities has the alteration of spontaneous become experimentally achievable.

The experimental investigation is strongly motivated by the recent developments of low-threshold VCSELs which contain ultra-small active volumes, and thus require ultra-low current values to achieve population inversion. Even without any reduction in threshold current due to controlled spontaneous emission, the ultra-small active volumes achievable in the quantum well VCSEL hold promise of lasing threshold currents in the tens of microamps. Presently, however, severe technical problems including lack of sufficient cavity Q, high electrical series resistance, and difficulties in current confinement have limited threshold currents of VCSELs to values well above there seemingly low microamp limit.

B.   PROGRESS: On the theoretical side, we now feel that we have a very good understanding of the features of spontaneous emission in semiconductor microcavities most relevant to the semiconductor laser [1,2]. We have been able to derive a model for lasing in a general Fabry-Perot laser which begins with a single spontaneous emission event, and follows the evolution of the spontaneous photon into the lasing emission [3]. Our analysis reproduces two important features of large Fabry-Perot cavity lasers, the Schawlow-Townes power-linewidth product expression for an ideal laser cavity and the linewidth enhancement factor due to the nonorthogonality of longitudinal cavity modes [4]. For microcavity lasers just how the cavity enhanced spontaneous emission enters into the threshold equation is as yet unclear. Einstein's relationship between spontaneous emission into an optical mode and stimulated emission into an optical mode must be achieved for thermodynamical laws to hold, but the definition of the optical modes for which this law must hold is a current source of confusion in ours and others works. We

note that the standard approach of simply solving Maxwell's classical equations for normal modes is hampered by the output coupling which exists from the cavity. We are continuing our theoretical investigations into this problem.

The experimental investigations have taken two avenues, as far as laser devices are concerned. The cavity effects are largest for the smallest optical cavities. For cavities with dielectric stack reflectors (necessary for high optical Q), the cavity volume is severely limited by the contrast ratio of the refractive index of the mirror materials. The highest contrast mirrors, which result in the smallest cavity lengths and thus smallest cavity volumes, are based on insulating materials and necessitate optical pumping for excitation of the laser active medium. We fabricate such semiconductor cavities, which have cavity thicknesses of $\sim$ 0.25μm, from epitaxial layers of AlGaAs-GaAs and use electron-beam deposited CaF-ZnSe to realize high reflectivity, high contrast Bragg reflecting mirrors to achieve short cavity lengths. The semiconductor lasers are excited with a tunable, mode-locked Titanium Sapphire layer, and the semiconductor laser output is characterized to determine threshold and spectral response, as well as far-field radiation pattern. The semiconductor laser layer structures are designed to both short ($\sim$0.25μm) and long ($\sim$5 to10μm) cavity lasers to be directly compared from the same semiconductor layer. Initial results show significantly lower thresholds in the short cavity lasers for structures tested so far. However, interpretation of the data is not clear cut without detailed knowledge of later loss effects due to cavity length in the semiconductor lasers. Current work is focussed on determining quantitatively the lateral loss characteristics of the devices through measurements of the far-field radiation patterns. Work is also underway on measuring the frequency response of the lasers, through gain switching, to assist in the determination of gain enhancement due to the optical cavity. Details of this work will be presented at the Quantum Optoelectronics Topical Meeting, March 17-19, 1993, in Palm Springs [5].

From a more practical point of view, we are developing VCSEL designs directed towards lateral confinement of the current into the laser active region. Our most recent work has focussed on the incorporation of semi-insulating AlGaAs layers, using low-temperature molecular beam epitaxy, into the VCSEL for p-side current confinement. This investigation has met with considerable success, and we have realized relatively low threshold, high efficiency, low resistance lasers which rival the continuous wave performance yet achieved anywhere. Threshold voltages as low as 1.8V for 3mA devices has been achieved, with CW output powers of over 6mW at a wavelength of 0.98μm. The details of these devices have been reported at the 12th North American Conference on Molecular Beam Epitaxy, Oct.12-14, 1992, in Ottawa, Canada [6], and in a late paper at the IEEE/LEOS Annual Meeting, November 15-20 in Boston [7]. Work is now directed towards achieving a buried active region of small diameter (<6μm) using the low temperature molecular beam epitaxy regrowth technique.

C. FOLLOW-UP STATEMENT: The continuing work involves the theoretical investigation of how the controlled spontaneous emission may modify the laser gain equations, the experimental study of short-cavity photopumped semiconductor lasers, and the experimental realization of small diameter current confined VCSELs.

D. REFERENCES:

[1]   D.G. Deppe and C. Lei, Appl. Phys. Lett. **60**, 527 (1992).

[2]   Z. Huang, C. Lei, D.G. Deppe, C.C. Lin, C.J. Pinzone, and R.D. Dupuis, Appl. Phys. Lett. **61**, 2961 (1992).

[3]   D.G. Deppe, "Near-Threshold Lasing Characteristics in Fabry-Perot Cavities and Microcavities", submitted to Phys. Rev. A.

[4]   W.A. Hammel and J.P. Woerdman, Phys. Rev. Lett. **64**,1506 (1990).

[5]   D.L. Huffaker, D.G. Deppe, C.J. Pinzone, T.J. Rogers, B.G. Streetman, and R.D. Dupuis, "Threshold Dependence on Cavity Length and Mirror Reflectivity in Fabry-Perot Microcavity Semiconductor Lasers with High Contrast Mirrors", Quantum Optoelectronics Topical Meeting, March 17-19, 1993, Palm Springs, accepted.

[6]   T.J. Rogers, C. Lei, B.G. Streetman, and D.G. Deppe, "Low Growth Temperature AlGaAs Current Blocking Layers for Use in Surface Normal Optoelectronic Devices", 12th North American Conference on Molecular Beam Epitaxy, Oct.12-14, 1992, Ottawa, Canada.

[7]   C. Lei, T.J. Rogers, D.G. Deppe, B.G. Streetman, "Low-Threshold-Voltage CW Vertical-Cavity Surface-Emitting Lasers Based on Low Growth Temperature Current Blocking Layer", IEEE/LEOS Annual Meeting, November 15-20, Boston, Post-Deadline Paper, PD4.

E.   PUBLICATIONS AND CONFERENCE PRESENTATIONS:

I.   LIST OF PUBLICATIONS:

1.   D.L. Huffaker, D.G. Deppe, C. Lei, T.J. Rogers, B.G. Streetman, S.C. Smith, and R.D. Burnham, "Cascadability of an Optically Latching Vertical-Cavity Surface-Emitting Laser", Electron. Lett. 28, 734-736 (9 April, 1992).

2.   T.J. Rogers, C. Lei, B.G. Streetman, and D.G. Deppe, "Low Growth Temperature AlGaAs Current Blocking Layers for use in Surface Normal Optoelectronic Devices", J. Vac. Sci. Tech., accepted.

3.   T.J. Rogers, C. Lei, D.G. Deppe, and B.G. Streetman, "Low Threshold Voltage CW Vertical-Cavity Surface-Emitting Lasers", submitted to Appl. Phys. Lett.

4.   D.G. Deppe, "Near-Threshold Lasing Characteristics in Fabry-Perot Cavities and Microcavities", submitted to Phys. Rev. A.

5.   Z. Huang, C.C. Lin, and D.G. Deppe, "Spontaneous Lifetime and Quantum Efficiency From Light Emitting Diodes Affected by a Close Metal Mirror", submitted to IEEE J. Quant. Electron.

6.   D.G. Deppe, C. Lei, D.L. Huffaker, and C.C. Lin, "Spontaneous Emission From Planar Microstructures," submitted to J. Mod. Optics.

II.   LIST OF CONFERENCE PROCEEDINGS AND PRESENTATIONS

1.   (Invited) D.G. Deppe, C. Lei, D.L. Huffaker, Z. Huang, C.C. Lin, "Spontaneous Emission in Semiconductor Microcavities", Rank Prize Fund Minisymposium, September 21-24, 1992, Grasmere, England.
2.   T.J. Rogers, C. Lei, B.G. Streetman, and D.G. Deppe, "Low Growth Temperature AlGaAs Current Blocking Layers for Use in Surface Normal Optoelectronic Devices", 12th North American Conference on Molecular Beam Epitaxy, Oct.12-14, 1992, Ottawa, Canada.

3.   C. Lei, T.J. Rogers, D.G. Deppe, B.G. Streetman, "Low-Threshold-Voltage CW Vertical-Cavity Surface-Emitting Lasers Based on Low Growth Temperature Current Blocking Layer", IEEE/LEOS Annual Meeting, November 15-20, Boston, Post-Deadline Paper, PD4.

4. C. Lei, D.G. Deppe, Z. Huang, C.C. Lin, C.J. Pinzone, and R.D. Dupuis, "Spontaneous Emission Characteristics from Dipoles with Fixed Positions in Fabry-Perot Cavities", 15th International Conference on Lasers & Applications, Dec. 7-11, 1992, Houston.

5. (Invited) D.G. Deppe, "Electrodynamics in Semiconductor Microcavity Lasers", Workshop on Optical Properties of Mesoscopic Semiconductor Structures, April 20-23, 1993, Snowbird, Utah, to be presented.

III. GRANTS AND CONTRACTS:

D.G. Deppe, "Bistability in VCSELs on GaAs and Si Substrates," Office of Naval Research, Young Investigator Award, Contract No. N00014-91-J-1952.

D.G. Deppe, "Electrodynamics in Semiconductor Microcavities," National Science Foundation Presidential Young Investigator, Contract No. ECS-9157190.

R.D. Dupuis, D.G. Deppe, and C.M. Maziar, "Optoelectronic Integrated Transmitter," Army Research Office, Contract No. DAAL 03-91-G-0163 .

B.G. Streetman and D.G. Deppe, "Low-Threshold Vertical-Cavity Surface-Emitting Lasers," Texas Advanced Technology Program, Contract No. TATP-076.

THE UNIVERSITY OF TEXAS AT AUSTIN   ELECTRONICS RESEARCH CENTER
                                          SOLID STATE ELECTRONICS

Research Unit SSE92-3:   Microcavity Photodetectors

Principal Investigator: Professor Joe C. Campbell (512) 471-9669

Graduate Students: R. Kuchibhotla and K.-F. Lai

A. SCIENTIFIC OBJECTIVES: The objective of this work is to design, fabricate, and characterize new photodetectors that utilize microcavity structures to achieve enhanced performance relative to conventional photodetectors. This will be accomplished by using recently-developed crystal growth techniques (Res. Unit SSE92-1) to incorporate elements such as Bragg mirrors into p-i-n photodiode and avalanche photodiode structures in order to improve their performance and functionality. As an example of this approach, we have recently demonstrated a novel resonant-cavity photodiode structure that decouples the quantum efficiency from the transit-time. The primary thrusts of the proposed research program will be (1) to study the device physics that delimits the performance of these microcavity photodetectors, (2) to demonstrate the performance advantages of this approach for a variety of materials and types of photodetectors , and (3) to utilize the characteristics of microcavity photodiodes to perform additional functions such as frequency discrimination for high-density multiplexing of fiber optic signals.

B. PROGRESS: The performance of conventional photodiodes is limited by an intrinsic tradeoff between quantum efficiency and bandwidth. We have successfully demonstrated that microcavity photodetectors with very thin absorption regions can achieve high quantum efficiencies. The microcavity approach increases the absorption through multiple reflections between two parallel mirrors. A schematic cross section of this type of photodiode is shown in Fig. 1. The lower mirror is an integrated Bragg reflector consisting of alternating $\lambda/4$ epitaxial layers similar to that used in vertical-cavity surface-emitting lasers. The ability to fabricate this type of integrated mirror is a direct result of the capability of molecular beam epitaxy (MBE) to grow stacks of very high quality epitaxial layers. In order to achieve high reflectivity, both the thickness and composition of the $\lambda/4$ pairs must be controlled precisely. Using the MBE system described in Unit SSE92-1 we have routinely obtained mirror reflectivities >99%. The top mirror is a high reflectivity dielectric stack that can be deposited after the crystal growth, fabrication, and initial characterization.

Prior to the start of this program we demonstrated the operation of the resonant cavity photodiode using an AlAs/GaAs Bragg reflector for the lower mirror (R > 99%) and a $CaF_2/ZnSe$ dielectric stack for the top mirror (R ≈ 73%) [1]. The absorbing layer was a 900Å-thick strained layer of $In_{0.05}Ga_{0.95}As$. A peak efficiency as high as 50% was obtained at λ = 840 nm. This compares favorably with the value of 8% in similar photodiodes that did not have the Bragg reflectors. The electric field in the thin $In_{0.05}Ga_{0.95}As$ layer increases rapidly with increasing bias. As a result, avalanche gain was achieved at very low voltages. Near the breakdown of 9 volts multiplication values as high as 200 were observed. The operating voltage of this APD was 4 times lower than any APD reported to date and it is comparable to the bias requirement of conventional p-i-n photodiodes.
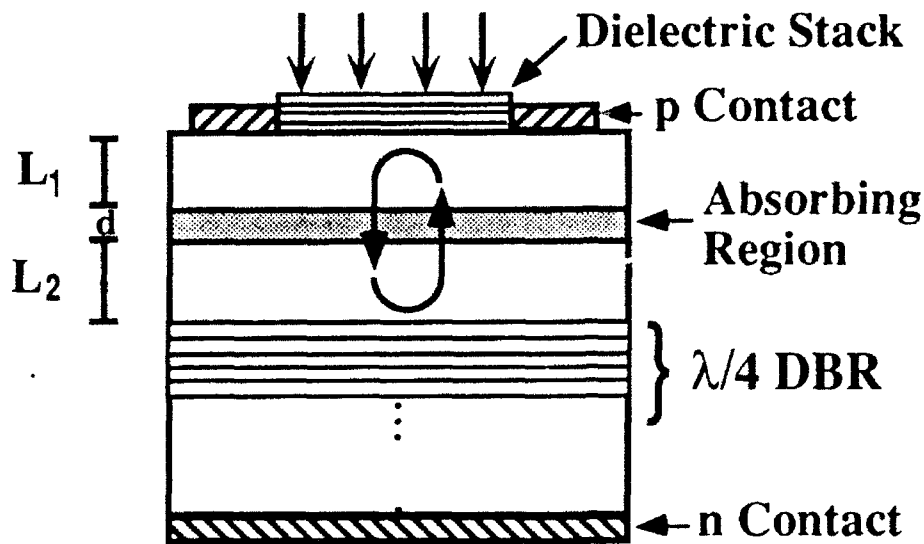
Figure 1. Schematic cross section of a resonant-cavity photodiode.

Much of the work on optical communications has focused on transmission at wavelengths where optical fibers exhibit low attentuation and minimum dispersion, namely, 1.3 μm and 1.55 μm. As a result, it was of crucial importance to extend our previous resonant cavity photodiode work to materials and structures that will operate at these longer wavelengths. In the InP/InGaAsP material system the refractive index step between the epitaxial layers in the Bragg mirror is not as large as that for AlAs/GaAs and therefore more pairs are required for high reflectivity. This is a concern because experimentally it is often difficult to maintain good material quality for a very large number of layers. Nevertheless, we have demonstrateu the first InP-based resonant-cavity photodiode [2].

The structure was grown by atmospheric pressure MOVPE in two steps. First, a quarterwave stack consisting of 20 periods of alternating InP and InGaAsP (λ_g = 1300 nm) layers was grown. The peak reflectivity was 95 % for 20 periods. After reflectivity measurements, the wafers were ie-inserted into a clean reactor for growth of the active region on top of the mirror stack. The active region consisted of a double heterojunction, with InP acting as the wide band-gap layer and $In_{0.53}Ga_{0.47}As$ serving as the absorption layer. The InP layers were 3200 Å thick while the InGaAs absorption region (n ~ 7 x 10^{15} cm^{-3}) had a layer thickness of 2000 Å. The reflectivity of the top surface was increased to 69% by depositing a single quarterwave pair of ZnSe/CaF$_2$.

Assuming an absorption coefficient of 0.70 μm^{-1} for InGaAs at 1480 nm, the quantum efficiency without the cavity enhancement would be expected to be approximately 14%. However, the actual measured quantum efficiency of the resonant-cavity structure was 82 %, close to the theoretically expected value of 83 % for a microcavity with top and bottom mirror reflectivities of 69% and 95%, respectively.

Ancther approach for extending the operating wavelength to the range currently being used for optical communications is to develop the SiGe/Si materials system. In collaboration with J. C. Bean at AT&T Bell Laboratories we have fabricated G_xSi_{1-x}/Si Bragg reflector mirrors [3]. These structures were grown in a Si-MBE system. Column IV mirror designs are constrained by the small refractive index between Si and Ge$_x$Si$_{1-x}$ alloys and the limitations of strained layer epitaxy that can produce misfit dislocations in thick mirror stacks. Despite these limitations, we have obtained mirrors with reflectivities over 70% at 1.5 μm. This will be appropriate for the "top" mirror in the resonant-cavity structure. In addition, we have

incorporated the Bragg mirror in a p-i-n photodiode structure. At present, the efficiency is below expectations, probably due to dislocations from the discommensurate mirror. Work is in progress to fabricate dislocation-free mirrors.

One of the attractive features of microcavity photodetectors is their potential for additional functions such as frequency discrimination for high-density multiplexing of fiber optic signals. Recently, we have designed a novel structure for an electrically tunable photodetector [4]. It employs both the quantum confined Stark effect of GaAs/AlGaAs multiple quantum wells and a resonant cavity structure to achieve wavelength selectivity and a large tuning range. The photodetector can be operated in two modes, namely the electrorefraction mode and the electroabsorption mode. In the electrorefractive mode, the change in refractive index with respect to the applied field is used to shift the resonant wavelength but the tuning range is estimated to be only 5nm. For the electroabsorption mode, on the other hand, the shift in the exciton peak corresponds directly to the shift in the operating wavelength and a tuning range up to 20nm is predicted. Our calculations show that there is a tradeoff between the crosstalk ratio and the peak efficiencies of the channels. It was found that an optimized structure would exhibit peak efficiencies in the range 40% to 55% while the crosstalk ratio of one channel is < -5dB and the other is < -16dB. We suggest that further improvements in device performance could be achieved by using narrower well widths or a strained layer structure. This kind of structure can also be extended to other material systems if other operating wavelength ranges are desired.

C. FOLLOW-UP STATEMENT: We will continue to work on the InP-based resonant-cavity p-i-n photodiodes. We have demonstrated near-theoretical quantum efficiencies and will now shift the emphasis to bandwidth measurements. To date, we have been limited in the speed measurements because we did not have a suitable excitation source. We now have a Ti-sapphire laser that can provide 150 fs pulses. As soon as our new optical laboratories are functional we will begin this characterization. We hope to continue our collaboration with AT&T Bell Laboratories on the development of Si-based structures. The well-known advantages of the Si materials system make this an attractive prospect. Work on the multiple-quantum-well, tunable photodiode has shifted to experimental verification. We have obtained MBE-grown wafers and are in the process of fabricating and characterizing the photodiodes.

I. LIST OF PUBLICATIONS

Journal Articles (* denotes a publication supported by JSEP).

1. R. Kuchibhotla, A. Srinivasan, J. C. Campbell, C. Lei, D. G. Deppe, Y. S. He, and B. G. Streetman, "Low-Voltage, High-Gain Resonant Cavity Avalanche Photodiode," *Photonics Tech. Lett.* 3, April 1991.

2. A. G. Dentai, R. Kuchibhotla, J. C. Campbell, C. Tsai, and C. Lei, "High Quantum Efficiency, Long Wavelength InP/InGaAs Microcavity Photodiode," *Electron. Lett.* 27, pp. 2125-2126, 1991.

3. *R. Kuchibhotla, J. C. Campbell, J. C. Bean, L. Peticolas, and R. Hull, "Ge0.2Si0.8/Si Bragg-Reflector Mirrors for Optoelectronic Device Applications," to be published in *Applied Physics Letters*.

4. *Kafai Lai, and Joe C. Campbell, "Design of a Tunable GaAs/AlGaAs Multiple Quantum Wells Resonant Cavity Photodetector ," submitted to *IEEE J. Quantum Electronics*.

II. LIST OF THESES AND DISSERTATIONS

Ph.D.

R. Kuchibhotla, "New Photodetectors for Optical Communications: Physics, Fabrication, and Characterization," December 1992.

III. CONTRACTS AND GRANTS

J. C. Campbell and D.-L. Kwong, "Ge_xSi_{1-x}/Si Optoelectronic Devices and Integrated Circuits," National Science Foundation, Contract ECS-9101187, January 1,992 - December 31,1994.

J. C. Campbell and D.-L. Kwong, "Ge_xSi_{1-x}/Si Integrated Photoreceiver," Office of Naval Research, Contract N00014-92-J-1085, January 1,992 - December 31,1993.

J. C. Campbell, "Microcavity Photodetectors," Texas Advanced Technology Program, Contract 003658412, January 1,1992 - December 31,1993.

J. C. Campbell and A. F. Tasch, "Si and Ge_xSi_{1-x} Light Emitting Devices," Texas Advanced Research Program, Contract 003658178, January 1,1992 - December 31,1993.

THE UNIVERSITY OF TEXAS AT AUSTIN   ELECTRONICS RESEARCH CENTER
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Research Unit SSE92-4   CHARGE TRANSPORT THROUGH AND ACROSS
                          HETEROBARRIERS

Principal Investigator: Christine M. Maziar (471-3674)

Graduate Students: Mahbub Rashed and Andalib Chowdhury

A.   Scientific Objectives: The focus of this research unit is the study of charge transport in semiconductors on ultra-short spatial and temporal scales. The understanding and exploitation of promising materials and devic concepts is most fully realized when accurate models are available to device researchers and materials scientists. Such models are most successfully developed when a simulation effort is tightly coupled with the results and needs of ongoing experimental efforts.   Such coordination has been demonstrated by and is a key feature of the research undertaken in this unit. As the description of our progress over the last year will show, our choice of focussing on transport related to heterobarrier/interfacial transport has provide ample opportunity to collaborate with other researchers in the UT-Austin JSEP. We continue to focus our efforts at developing a better understanding of transport across finite superlattices (that is superlattices composed of only a few periods). We have achieved some success in describing the bandstructure of these structures and turn an increased amount of our attention to transport problems. Such superlattice structures have frequently been proposed for advanced electronic and optoelectronic devics, however full exploitation of materials growth capabilities has been limited by available simulation tools. Our objective is to develop a tool which will permit efficient and routine calculaton of electonic bandstructure for finite superlattices and make that tool available to device resarchers interested in using it for the purpose of epilayer design for advanced device structures.

B.   Progress: In support of Mike Downer's (SSE92-5) femtosecond photoemission studies, we have constructed a software tool capable of simulating the evolution of a photoemitted distribution of charge.   This simulator is capable of studying the influence of a variety of experimental variables as well as physical phenomena on the distribution measured in the experiment. This simulator was constructed in such a fashion that it is possible to include the detail of image charge, emission time, multi-photon processes, distribution temperature and photoexcitation pulse width.   Initially, the purpose of our simulations was to explore the relationship between near-surface distribution functions and detected distribution functions in order to establish the level of correlation that can be established between a detected photoemitted distribution and surface distribution temperatures. In fact, our work has yielded rich insight into the short time-scale photoemission processes. We have been able to successfully reproduce the major features of the detected carrier distribution functions on both very short and modest time scales. The simulations together with the experimental work of Downer's (SSE92-5) group has yielded a clearer understanding of the relationship between multi-photon and thermionic emission processes. We determined that thermionic emission is the principal emission mechanism but that a small (but significant) fraction of the total yield originates from multiphoton emission resonantly enhanced by surface states.   A manuscript is currently in preparation describing both our simulator and the results of the study. We believe that the ability of our simulator to accurately reproduce experimental results provides experimentalists with yet another tool to use to interpret their data.

We have developed a sophisticated group of modeling and simulation tools for describing impact ionization in both III-V and IV semiconductor materials. Detailed models of this sort are necessary in order to fully exploit the materials growth (and design) capabilities of the center in applications for

advanced semiconductor device concepts. During the past year, we included a detailed description of impact ionization in a Monte Carlo code developed by our group in order to study possible anisotropy in the impact ionization rates of InP. This has been a somewhat controversial issue which we believe is now resolved. Our conclusion is that unstrained InP shows no anisotropy in the impact ionization rate. However, an extension of our model to include strain effects in InP suggests a possible source of the disagreement in the literature. Our simulations show that the presence of strain alters the threshold energies for impact ionization. Typically, the threshold energies vary from -0.75 to +0.4 eV (over the Brillouin zone) for a biaxial compression of 2%. As expected the impact ionization rates showed the greatest sensitivity to strain effects at low electric fields. For fields greater than 600 kV/cm, the changes in ionization rate with strain are less than 10%. For compressive strain, the electron ionization coefficient a, was evaluated to be 1.5×10^3 cm^{-1}, at an electric field of 400 kV/cm, which is about 70% less than that of unstrained material. For tensile strain the ionization coefficient was evaluated to be 1.0×10^4 cm^{-1} at the same field (or an increase of 130% over that of unstrained material). We plan to design an experimental structure to verify these results with the device fabrication and measurement expertise of Joe Campbell's group and the materials growth capabilites of Professor Russ Dupuis of UT-Austin.

In support of experimental work conducted in Joe Campbell's lab (SSE92-3) using materials grown by Sanjay Banerjee and Al Tasch of UT-Austin, we have evaluated and accurately simulated quantum confined Stark shifts in Si_xGe_{1-x}/Si quantum well structures at room temperature. The band alignment of these structures studied was of the staggered type II (i. e. the band edges of the narrower band gap $Si_{0.6}Ge_{0.4}$ lie above the respective band edges of the wider gap Si). Under applied electric field (ε), the change in transition energy shift may be expressed as $\Delta E_l + \Delta HH_1 \pm e\varepsilon L$ ($\Delta E_l + \Delta HH_1$ is the shift of minimum bound state energies). The last term represents the potential drop between the center of two adjacent layers and dominates the expression. The total energy shift is nearly linear, leading to large transition shifts[1]. Plotting Ihn as a function of hn, it is observed that near 800 meV (the estimated transition energy of the MQW), a varies as $(h\nu-Eg_0)^{1/2}$ for different applied electric fields. From this fit, the absorption edge (Eg_0) may be estimated at different electric fields. A linear edge shift towards lower energies with increased electric field may be observed. Good agreement is found between the experimentally obtained shift and that calculated within the framework of the envelope function approximation[2], neglecting intervalley interaction. The bandoffsets were estimated from the combination of self-consistent *ab initio* pseudopotential results[3] and the phenomenological deformation potential theory[4]. To understand the spectra at higher energies, we subtracted the $(h\nu-Eg_0)^{1/2}$ dependency from the measured data and obtained the absorption shape of the $Si_{0.8}Ge_{0.2}$ buffer layer.

In summary, we have demonstrated the utility of our bandstructure calculation tool by accurately predicting a previously unobserved, large linear quantum confined Stark shift in $Si_{1-x}Ge_x/Si$ MQWs at room temperature.

Recently, Ohno et al. [5] experimentally observed the presents of localized "Tamm"-like "surface" states in a finite GaAs/AlGaAs SL terminated by AlAs barriers at the end. In our work, we developed a model to calculate these SL surface states from a tight binding description of the envelope functions. In our model, the SL energy bands are derived from a know electron state in an isolated quantum well (QW). The presence of the remaining wells of the SL is expressed in the form of a perturbation. The termination of the periodic potential is introduced by a shift integral for the end well which differs from the shift integral of the other wells. The shift and transfer integrals are derived analytically in terms of isolated QW wave functions only. We find the presence of localized states inside the minigaps. These SL surface states may prove to be important in SL device applications as well as in the study of surface and interface physics.

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C. Follow-Up Statement: We will continue to assist Downer's group with simulation of the femtosecond photoemission processes. However, we plan to develop a "user-friendly" version of the code so that we can deliver the tool to Downer's lab for use by his graduate students. Our plans for the coming year include moving our simulation activities into the study of photoemission from semiconductor surfaces and include more detail of the surface potential interaction with the photoemitted electrons. The particular material system studied will in large part be governed by the interests of the experimental group.

The work involving impact ionization modeling in III-V semiconductors is moving into the arena of studies of impact ionization in multi-quantum wells and of impact ionization in dimensionally reduced structures. We will explore this reduced dimensionality in two senses. The first is the effect that a quantum confinement structure has on impact ionization rates and the second is the effect that a reduced length multiplication region has on the estimation of experimentally determined impact ionization rates. We are particularly interested in the role that multiquantum well structures play in enhancing or suppressing impact ionization of electrons and holes. In order to study the hole transport problem, we will need to modify our simulator to include the transport of carriers in the valence band. A question which we hope to answer in the coming year is whether a simple "equivalent alloy" model is acceptable for modeling impact ionization in high fields in multiquantum well structures. Such a finding would greatly simplify the analysis of multiplication regions in a variety of avalanche photodetectors (APDs) proposed in the literature. The work in relating materials characteristics with device performance will be done in collaboration with Joe Campbell.

The tight binding approach we have used in earlier work has the advantage of simplicity, ut it is not fully justified since we have neglected the hybridization of states originating from the fundamental quantum-well bound state with all the other (bound and unbound) states. For given SL period, the energy bands derived from the ground state and the excited states of the isolated QWs may overlap and even can get "crossed". Then, Shockley-like surface states may appear as was argued by Shockley for bulk solids. Such thin barriers are commonly used in SLs for electroabsorptive devices. The short transit times are instrumental in leading to fast photodetectors, modulators and switching devices. Short transit times are also useful in reducing the surface recombination effects which are present in small devices. Additionally, the much publicized Wannier-Stark localization is inherently dependent on the efficient interwell coupling. Reducing the barrier width also decreases the overall thickness of the activelayer, therefore external voltage and power consumption required to obtain desired electric fields can be minimized. We believe that the prediction o f Shockley-type surface states in these SL structures may provide important new insights. The existence of these surface states and their sensitivity to varying surface potentials may provide a sensitive means of probing these surface potentials. We propose to identify or determine the existence of these Shockley states from the tight binding description of the envelopes as well as from the Evenelope Function Approximation as we accomplished for the calculation of Tamm-like SL surface states.

We also plan to extend the methods we have formaulated thus far to include the effect of the coupling of different intervalley transfer, different base SLs and polytype SLs. The methods will also be extended for type II $Si/Si_{1-x}Ge_x$ and InAs/GaSb SLs. Interesting new physics of type II SL surface states is expected particularly under the applicationof an electric field. One major difference is the enhancement of optical transition probability in type II SLs under electric field as opposed to the case of type I SLs. Additionally, we propose to explore the influence of strain at the interface on the creation of and energies of interfacial surface states.

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E.I. List of Journal Publications (*JSEP supported in whole or in part)

* V. Chandramouli and C. M. Maziar, "Impact Ionization Energy Thresholds Throughout the First Brillouin Zone in InP," accepted for publication in *Solid State Electron.*

T. J. Bordelon, V. M. Agostinelli, X.-L. Wang, C. M. Maziar and A. F. Tasch, "The Relaxation Time Approximation and Mixing of Hot and Cold Electron Populations," *Electronics Letters,* pp.1173-1175, June 4, 1992.

* Xiaolin Wang, V. Chandramouli, Christine M. Maziar and Al F. Tasch, Jr., "SLAPSHOT: An Efficient Multi-Band Monte Carlo Model Using Both Full and Analytic Bandstructure Description for Silicon, " accepted for publication in *J. Appl. Phys.*

E.II. List of Conference Proceedings (*JSEP supported in whole or in part)

* Andalib Chowdhury and C. M. Maziar, "Modeling of the superlattice surface states from the envelope function approximation using a multiband Hamiltonian" *Proceedings SPIE 1992 Symposium on Compound Semiconductors and Devices/ Quantum Wells and Superlattices,* vol. 1675, pp. 398-394, March 23-27, 1992, Somerset, New Jersey, .

Xiao-Lin Wang, Venkatraman Chandramouli, T. James Bordelon, Christine M. Maziar and Al F. Tasch, Jr., "Influence of Silicon Bandstructure on Transport Coefficient Models for Hydrodynamic Simulation,"(invited paper), *Proceedings of NASECODE VIII,* pp. 52-53, May 20-22, Vienna, Austria.

* M. Reaz Shaheed and C. M. Maziar, "Extension of Common-Emitter Breakdown Voltage for High Speed Si/Si$_{1-x}$Ge$_x$ HBTs," presented at *IEEE Bipolar Technology Meeting,* October 4-6, 1992, Minneapolis, MN.

* X. L. Wang, V. Chandramouli, Christine M. Maziar and A. F. Tasch, "An Efficient Multi-Band Monte Carlo Model With Anisotropic Impact Ionization," presented at the *1992 IEDM,* December 13-16, 1992, San Francisco, CA.

* Andalib A. Chowdhury, M. Mahbub Rashed, C. M. Maziar, S. S. Murtaza and J. C. Campbell, "Observation of room temperature quantum confined Stark shift in Si$_{1-x}$Ge$_x$/Si multi-quantum wells," presented at the *Twentieth Conference on the Physics and Chemistry of Semiconductor Interfaces (PCSI-20),* January 25-29, 1993, Williamsburg, VA.

* X. Y. Wang, D. M. Riffe, M. C. Downer, J. L. Erskine, D. L. Fisher, T. Tajima, M. Rashed, C. M. Maziar and R. M. More, "Electron Emission from Metal Surfaces Excited by Intense Femtosecond Pulses," accepted for *Short Wavelength V: Physics with Intense Laser Pulses,* *Optical Society of America,* March 1993, San Diego, California.

E. III.   List of Related Presentations (*JSEP supported in whole or in part)

*   A. Chowdhury and C. M. Maziar, " Modeling of 'Tamm'-like states in superlattices from a tight binding description of the envelope functions," presented at the March Meeting of the American Physical Society, March 16-20, 1992, Indianapolis, IN. (abstract published in *Bulletin of the American Physical Society*).

*   Andalib A. Chowdhury and C. M. Maziar, "A Simple Tight Binding Method Describing the Physics Behind the Formation of Superlattice Surface States," presented at *11th Annual Symposium on Electronic Materials, Processing and Characterization*, American Vacuum Society, June 1 and 2, 1992, Richardson, Tx.

V. Chandramouli and C. M. Maziar, "Effect of mismatch strain on impact ionization thresholds in InP," presented at *11th Annual Symposium on Electronic Materials, Processing and Characterization*, American Vacuum Society, June 1 and 2, 1992, Richardson, Tx.

A. F. Tasch and C. M. Maziar, "Parallel Computational Microelectronics," *Fifth Annual Computer Sciences Frontiers Symposium in High Performance Computing*, October 13-14, 1992, The University of Texas at Austin, Austin, TX.

E.V.   List of Grants or Contracts

National Science Foundation "Presidential Young Investigator Award," Professor Christine M. Maziar, Principal Investigator.

Semiconductor Research Corporation, "Analysis and Development of High Density MOSFET Structures for Deep Submicron CMOS/ULSI Technology," Professors C. M. Maziar and A. F. Tasch, Co-Principal Investigators.

National Science Foundation, "The Synthesis, Growth, and Analysis of Electronic Materials," The National Science Foundation as a Science and Technology Center, C. M. Maziar is a co-investigator with 12 others.

Hewlett-Packard Corporaton, "Equipment Grant", Professor C. M. Maziar, Principle Investigator.

United States Army Research Office, "Materials and Device Research for High-Speed Integrated Optoelectronic Transmitters Using Vertical-Cavity Surface Emitting Lasers,"Professors C. M. Maziar, Russel Dupuis and Dennis Deppe, Co-Principal Investigators.

National Science Foundation, "Pilot Project: Introduction to Electrical and Computer Engineering," Professor M. Gonzalez, Principal Investigator, Professors C. M. Maziar, M. Becker, L. Pillage, T. Wagner, G. Wise and M. Shermis(Educational Psychology) co-investigators.

National Science Foundation, "Adaptive Techniques Applied to the Solution of the Hydrodynamic Equations for Semiconductor Device Simulations," Professors C. M. Maziar and J. Kallinderis, Co-Principal Investigators.

National Science Foundation, "Research Careers for Minority Scholars," Professors C. M. Maziar and Joe Malina.

Research Unit SSE92-5:   FEMTOSECOND PHYSICS OF ELECTRONIC MATERIALS AND
                         DEVICES

Principal Investigator: Professor M. C. Downer (512) 471-6054

Graduate Students: X. Y. Wang and J. I. Dadap

A.   **SCIENTIFIC OBJECTIVES**: We seek insight into the physics of ultrafast processes in
technologically important solid materials, using the techniques of femtosecond laser
spectroscopy.   This knowledge base guides the simulation and development of new electronic
materials and devices. We also are developing noncontact, nondestructive, optical diagnostics
based on femtosecond laser sources which can be used as in situ monitors of semiconductor
growth and processing.

B.   **PROGRESS**:   Our study of femtosecond thermionic electron emission from metal surfaces
in ultrahigh vacuum (UHV), involving collaboration with J. L. Erskine (UT-Austin Physics) and more
recently with C. M. Maziar (Research Unit SSE92-4), was described at some length in last year's
annual report. This year a comprehensive, full length article on experimental and theoretical
aspects of this project was written up and submitted to the Journal of the Optical Society of
America B [1].   In addition, two invited [2,3] and two contributed talks [4,5] were presented at
international meetings. This work will comprise the bulk of the Ph.D. dissertation of JSEP-
supported student X. Y. Wang, expected to be completed during 1993. The content of these
papers, and of the past year's progress, can be summarized as follows:

Femtosecond laser pulse induced electron emission from W(100), Al(110), and Ag(111) in the
subdamage regime (1 to 45 mJ/cm^2 fluence) has been studied by simultaneously measuring the
incident light reflectivity, total electron yield, and electron energy distribution curves (EDC's) of
the emitted electrons. The total yield results are compared with a space-charge-limited extension
of the Richardson-Dushman equation for short time scale thermionic emission (analytic theory)
and with Particle in a Cell (PIC) computer simulations of femtosecond-pulse-induced thermionic
emission.   Quantitative agreement - a linear yield vs. temperature beginning at a threshold
electron temperature of ~0.25 eV - between the experimental and calculated temperature-
dependent yields from the analytic theory is obtained. Most significantly, the PIC simulation..
simultaneously reproduce the experimental EDC's and the experimental yields for peak electron
temperatures consistent with the reflectivity measurements. Taken together, the experiment,
analytic theory, and PIC simulations demonstrate that thermionic emission from nonequilibrium
electron heating provides the dominant source of the emitted electrons. Furthermore, the results
demonstrate that a quantitative theory of space-charge-limited femtosecond pulse induced
electron emission is possible.

Successful implementation of PIC simulations, and their quantitative comparison with
experimental results, was the major theoretical development of the past year on this project. The
simulation results reported in the above papers, performed in collaboration with T. Tajima (UT-
Austin Physics), used a nonrelativistic one dimensional (1D) code modified to simulate the three
dimensional (3D) axially symmetric geometry of the space immediately above the photoexcited
surface.   Thermionic electron emission rate was modelled with a standard Richardson formula.
This simulation successfully resproduced experimental temperature-dependent yields and the
high energy tails of experimental EDC's. More recently (not reported in above papers), in
collaboration with C. M. Maziar, a fully 2D (i.e. 3D axially symmetric) simulation code has been
adapted to this problem. The results reproduce temperature-dependent yields equally well, while
improving upon our model of the measured EDC's [6].

On the experimental side, the major development of the past year was completion of the reflectivity, total electron yield, and EDC measurements reported in the above papers. Since then, experiments have been extended to semiconductor surfaces. In addition, resonant surface state features observed throughout the reported data are being further investigated by using excitation at different wavelengths [7], by time-resolved experiments[8], and by surface harmonic generation experiments[9]. Finally, experiments are being conducted at higher intensity levels (fluence > 45 mJ/cm^2) above the damage threshold. Preliminary results show onset of ion emission starting at the damage threshold, as expected, as well as strong deviation of temperature-dependent-yield and EDC's from the behavior documented at sub-damage fluences. These deviations are believed to result from new (non-thermionic emission) electron acceleration mechanisms caused by interaction of the intense pump laser pulse with the developing density gradient at the hydrodynamically expanding solid surface [10,11], and are being further investigated. Study of suprathermal electron emission by femtosecond pulses in the above-damage regime is motivated by two applications. First, development of a high energy, high yield pulsed electron source for injection into particle accelerators [12 - 15], and secondly, a heating source for [16] or energy loss mechanism from [11] laser fusion targets.

Progress has continued with small signal, femtosecond reflectivity experiments, which are being developed as a characterization of semiconductor alloy and compound semiconductor films. Specific progress beyond the results described in the previous annual report includes the following: **1)** A report of femtosecond reflectivity measurements of single crystal, relaxed, optically thick Si_xGe_{1-x} epitaxial films was published [17]. The reported results were obtained with a previous generation, fixed frequency, colliding pulse mode-locked (CPM) dye laser, and samples across the entire compositional range were investigated. The reflectivity dynamics of the carefully screened relaxed, optically thick films appeared qualitatively to arise from intrinsic bulk carrier dynamics of the alloys. Several other samples with thinner epilayers of the same alloy compositions, but in which the film-substrate interface lay within the optical pumping and probing depth, showed reflectivity responses with much shorter recovery times (as short as 1 ps.). This extremely short response is believe to result from rapid carrier trapping caused by high defect densities in the interfacial region, similar to femtosecond reflectivity results in ion-implanted silicon [18] and low-temperature MBE-grown III-V semiconductors [19]. **2)** A complete rotating compensator femtosecond ellipsometry system has been developed and tested [20]. incorporating rapid-scan data acquisition techniques [21] described in a previous report, and mathermatical description and experimental verification of the criteria for optimizating measurement sensitivity to the time-varying dielectric function $\varepsilon_1(t) + i\,\varepsilon_2(t)$ in a wide variety of samples. The optimized system now in use in our laboratory measures probe reflectivity in a "PCSA" configuation - i.e. the probe beam passes through a polarizer (P) oriented at fixed angle, a continuously rotatable quarter-wave retardation optic (compensator C) before reflecting from the sample (S) at oblique angle of incidence. The reflected probe then passes through an analyzer (A) oriented at fixed angle before reaching the detector. Two (or more) independent, well-contrasted reflectance measurements are made by rotating the fast axis of the compensator to two (or more) strategically chosen orientations around the obliquely-incident probe beam axis. A comprehensive paper describing the femtosecond PCSA ellipsometer and its optimization criteria is now being prepared. **3)** The femtosecond ellipsometer has been applied to the complete family of Si_xGe_{1-x} samples. For above gap pumping and probing, the real $\varepsilon_1(t)$ and imaginary $\varepsilon_2(t)$ parts of the dielectric function both contribute to the reflectivity change. However, a conventional time-resolved reflectivity measurement [17,22] cannot distinguish their relative contributions. The femtosecond ellipsometric measurement determines $\varepsilon_1(t)$ and $\varepsilon_2(t)$ reliably, reproducibly, and with high signal-to-noise, thus providing a complete basis for modelling femtosecond carrier dynamics. **4)** A quantitative femtosecond carrier dynamics model for Ge and Si_xGe_{1-x}, based on a previous analytic model developed to explain picosecond time-resolved reflectivity measurements in these materials [23], has been developed. Four coupled Boltzmann transport equations for free carrier density, electron energy, hole energy, and lattice energy are solved simultaneously and numerically on a personal computer. The computational results

reproduce the broad features of $\varepsilon_1(t)$ and $\varepsilon_2(t)$ measured by femtosecond ellipsometry. However, not surprisingly, some revisions to assumptions which worked in modelling a picosecond time-resolved experiment [22,23] appear necessary to model quantitative details of the femtosecond ellipsometry results. At present, the most important revisions appear to be a) a time-varying reduced effective carrier mass $m^*(t)$ must be invoked to account for intervalley scattering which occurs in the first 2 ps., and b) band renormalization induced by the initially high carrier density is required to explain induced absorption transients in some of the alloys. These modelling details are still underway, and a paper describing them and the corresponding experiments is in preparation. The resulting model and comparison with experimental results will provide a basis for developing and testing more sophisticated Monte Carlo models of femtosecond carrier dynamics in Si_xGe_{1-x} (see Research Unit SSE92-4).

Acquisition and installation within the past year of a titanium-sapphire, femtosecond laser (Coherent Model Mira), which produces tunable femtosecond pulses fifty times more energetic than the CPM laser, has significantly expanded our femtosecond optical semiconductor diagnostic capabilities. Our expanded approach now aims to use this new light source to performs a triple function: 1. fixed angle spectroellipsometry, which uses the tunable output as a cw source, and provides the traditional diagnostic power of spectroellipsometry 2. femtosecond ellipsometry, described above, which correlates femtosecond carrier dynamics with growth-, process-, and strain-induced defects relevant to device quality, and 3. surface second harmonic generation (SHG) spectroscopy, which provides the primary diagnostic of surface chemistry and crystallography, and takes advantage of the high peak intensity of femtosecond pulses. Pulses from the previous generation CPM laser (unamplified) were too weak to yield surface SHG signals with adequate signal-to-noise for meaningful diagnostic experiments.

Initial SHG results with this new laser have now been obtained by JSEP-supported graduate student Jerry Dadap. First, the second harmonic spectrum in reflection of GaAs , and its rotational anisotropy, was measured over a wide range of near infrared fundamental frequencies. One- and two-photon resonant features were in good agreement with previous measurements made with low repetition rate, amplified dye laser systems[24]. However, our signal-to-noise is unprecedented because the unamplified MIRA laser generates second harmonic signal at 100 MHz repetion rate. For comparative second harmonic spectral measurements, a number of short period superlattice samples of the form $(GaAs)_m/(AlAs)_n$ have been obtained from Streetman (Research Unit SSE92-1). These spectra will be compared directly with theoretical calculations [25] which predict that unique superlattice features of the band structure will be more evident in the second harmonic spectrum than in the linear absorption spectrum. Period uniformity and interface roughness are also expected to influence the SHG measurement. Similar measurements are planned on short period $(GaP)_m/(AlP)_n$, and $(Si)_m/(Ge)_n$ superlattices, for which calculations are also available [26]. This type of measurement of subtle spectral features relies heavily on the tunability and the high signal-to-noise uniquely available by using the solid state femtosecond laser source.

Since III-V semiconductors are noncentrosymmetric in the bulk, this second harmonic signal is generated from a depth of $\lambda/2\pi = 10^{-5}$ cm beneath the surface, and thus is a bulk rather than surface-specific signal. This feature renders it several orders of magnitude stronger than the corresponding surface SHG in reflection from centrosymmetric Si, Ge, Si_xGe_{1-x}, diamond, and other Column IV materials. Recently, however, JSEP student Jerry Dadap has also observed surface SHG in reflection from a variety of Column IV materials using the femtosecond titanium-sapphire laser. Photon counting is needed, but counting rates are high, and signal-averaging times of less than one second per data point yield excellent signal-to-noise. Previously, such measurements were possible only with highly amplified, low repetition rate, long (ns. or ps.) pulsed Nd: YAG or dye laser systems, which placed severe limits on available signal-to-noise [27]. By contrast, our results from Si(111), Si(100), diamond surfaces show comparatively very high signal-to-noise. A good example is s-polarized second harmonic signals from Si(100), where we observe rotational anisotropy features with signal-to-noise of 100 or greater, whereas previous

investigators have obtained only "near unity" signal-to-noise [27]. Consequently detailed features of these signals can now be observed for the first time. For example, we have a strong dependence of the p-in, s-out surface SH signal from Si(100) on doping level. Specifically, nominally undoped Si(100) yields a 4-peaked rotational anisotropy, whereas n-Si(100) and p-Si(100) both yield 8-peaked rotational anisotropy, but with very different relative peak magnitudes. This preliminary result is being further investigated.

A technologically important application of the s-polarized SH signal, which we are now pursuing, is to develop a noncontact, noninvasive, optical diagnostic of $Si(100)/SiO_2$ gate oxide interface roughness. As device dimensions shrink, this interface roughness is a major source of dielectric breakdown in MOS devices. Early noncontact detection during processing is required. The rotationally isotropic component of the s-in, s-out SH signal, which is generated primarily within several atomic monolayers around the Si/SiO_2 interface [28], vanishes rigorously for an atomically smooth interface, but takes on nonzero values for a rough interface [29]. We have already observed substantial isotropic components to the s-in, s-out SH signals from uncharacterized $Si(100)/SiO_2$ samples. In the near future, we plan to perform more systematically controlled experiments in which these measuremen.. are performed on samples in which the interface roughness has been independently char. 'erized by atomic force microscope. Correlations between the two diagnostics will then be carefully examined, with the goal of developing a quantitative optical roughness diagnostic.

A comprehensive report of the work of JSEP-supported student David Reitze on the optical properties of the controversial liquid state of carbon, described in previous annual reports, has now been published in Physical Review B [30]. Shortly after its appearance, an article written by Nobel laureate Nicolaas Bloembergen, describing Reitze's JSEP-supported experiments, was published in the journal **Nature** [31].

C.   FOLLOW-UP STATEMENT: Femtosecond electron emission, ellipsometry, and second harmonic experiments will continue. The near term goals of each experiment have been described in the corresponding paragraphs above.

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II. LIST OF CONFERENCE PROCEEDINGS (* JSEP supported in whole or in part)

Refereed

* H. R. Choo, M. C. Downer, and V. P. Kesan, "Real-time femtosecond ellipsometry of Si_xGe_{1-x} epilayers." In Mechanisms of Heteroepitaxial Growth, M. F. Chisholm, B.J. Garrison, R. Hull, L.J. Schowalter (eds.) **Materials Research Society Symposium Proceedings** **263**, 317-322 (1992).

Non-Refereed:

* H. R. Choo, M. C. Downer, and V. P. Kesan, "Rapid-scan femtosecond ellipsometry of Si_xGe_{1-x} and C_{60} crystalline films." In **Quantum Electronics and Laser Science Conference,** 1992 OSA Technical Digest Series 13 (Optical Society of America, Washington, DC 1992), pp. 212-213.

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* X. Y. Wang, H. Ahn, and M. C. Downer, "Heating and hydrodynamic expansion of intensely irradiated metal targets measured by femtosecond time-resolved reflectivity." In **Quantum Electronics and Laser Science Conference,** 1992 OSA Technical Digest Series 13 (Optical Society of America, Washington, DC 1992), pp. 280-281.

III. LIST OF PRESENTATIONS (* JSEP supported in whole or in part)

(Presentations corresponding to above-listed conference proceedings are not repeated below.)

Invited Presentations:

M. C. Downer, "Hot, pressurized condensed matter created and probed by femtosecond laser pulses," **Japan-US Seminar on Physics of High Power Laser Matter Interactions,** Kyoto, Japan, 12 March 1992.

M. C. Downer, "Femtosecond ionization dynamics at atmospheric density measured by spectral blueshifting," **Japan-US Seminar on Physics of High Power Laser Matter Interactions,** Kyoto, Japan, 10 March 1992.

M. C. Downer, "Optical properties of pressurized fluids measured by femtosecond spectroscopy," **NATO Advanced Study Institute on Laser Interactions with Atoms, Solids and Plasmas,** Cargèse, Corsica, 19 August 1992.

* M. C. Downer, "Optical properties of hydrodynamically expanding solid surfaces measured by femtosecond spectroscopy," **NATO Advanced Study Institute on Laser Interactions with Atoms, Solids and Plasmas,** Cargèse, Corsica, 21 August 1992.

* M. C. Downer, "Femtosecond thermionic emission: experiment, analytic theory, and particle simulations," **NATO Advanced Study Institute on Laser Interactions with Atoms, Solids and Plasmas,** Cargèse, Corsica, 25 August 1992.

M. C. Downer, "Photon acceleration," **NATO Advanced Study Institute on Laser Interactions with Atoms,** Solids and Plasmas, Cargèse, Corsica, 27 August 1992.

M. C. Downer, "Optical properties of condensed matter under planetary interior conditions measured by femtosecond spectroscopy," Physics department colloquium, **Texas Tech University,** Lubbock, TX, 22 October 1992.

* M. C. Downer, "Femtosecond reflectance and electron emission experiments on intensely irradiated solid targets," **Lawrence Livermore National Laboratory,** X-Division seminar, Livermore, CA, 2 December 1992.

* M. C. Downer, X. Y. Wang, and H. Ahn, "Optical properties of condensed matter under planetary interior conditions measured by femtosecond spectroscopy," **International Conference on Lasers '92,** Houston, TX, 7 December 1992.

* M. C. Downer, D. M. Riffe, X.Y. Wang, D. L. Fisher, J. L. Erskine, "Femtosecond thermionic emission: a new regime of nonlinear photoemission," **International Conference on Lasers '92,** Houston, TX, 8 December 1992.

* M. C. Downer, " Femtosecond Lasers for Optical Characterization of Semiconductor Epilayers," **IEEE Lasers & Electro-Optics Society Meeting,** Microelectronics & Computer Consortium (MCC), Austin, TX, 13 January 1992.

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* H. R. Choo, J. Dadap, and M. C. Downer, "Femtosecond ellipsometry and second-harmonic probes of semiconductor epilayers," **SPIE OE LASE '93 Conference 1861B on Ultrafast Spectroscopy of Advanced Electronic and Optoelectronic Materials**, Los Angeles, CA, 22 January 1993.

Contributed Talks:

M. C. Downer, D. H. Reitze, and H. Ahn, "Electronic Properties of Liquid Carbon derived from Femtosecond Optical Spectroscopy." Presented at **Materials Research Society Meeting**, San Francisco, CA, 27 April 1992.

* M. C. Downer, D. M. Riffe, X. Y Wang, J. L. Erskine, D. L. Fisher, T. Tajima, and R. M. More, "Femtosecond thermionic emission: experiment, analytical theory, and particle simulations." Presented at **8th International Conference on Ultrafast Phenomena**, Antibes, France, 11 June 1992.

* X. Y. Wang, H. Ahn, and M. C. Downer, "The role of covalency in femtosecond time-resolved reflectivity of hydrodynamically expanding solid surfaces." Presented at **8th International Conference on Ultrafast Phenomena**, Antibes, France, 11 June 1992.

IV.   LIST OF THESES AND DISSERTATIONS

M.S.

Guo Wei, " Femtosecond Ellipsometric Analysis of Semiconductor Epilayers," May 1992.

Ph.D.

Heung Ro Choo, "Rapid Scan Femtosecond Ellipsometry and its Application to Optical Surface Diagnostics and Ultrafast Carrier Dynamics in Semiconductors," December 1992.

V.   CONTRACTS AND GRANTS

M.C. Downer, "Femtosecond Processes in Condensed Matter," National Science Foundation (Presidential Young Investigator Award), Grant DMR-8858388, June 1, 1988 - December 31, 1993.

J.M. White (P.I.), National Science Foundation (Science and Technology Center), "Synthesis, Growth, and Analysis of Electronic Materials"; M.C. Downer is one of 13 UT Austin faculty participants in this Center.

M.C. Downer, "Femtosecond Angle-Resolved Photoemission Spectroscopy of Electronic Materials," Office of Naval Research (Young Investigator Award), Contract N00014-88-K-0663, October 1, 1988 - September 30, 1992.

M.C. Downer, "Femtochemistry of Surfaces in Transition," Robert A. Welch Foundation, Grant F-1038, June1, 1992 - May 31, 1995.

M.C. Downer, "In Situ Femtosecond Ellipsometer Probe of Semiconductor Crystal Growth", Texas Advanced Technology Program, Grant No. 399, January1, 1992 - December 31, 1993.

T. Tajima and M. C. Downer, "Laser Wakefield Excitation and Measurement on a Femtosecond Time Scale: Theory and Experiment," Department of Energy, Grant DEFG05-92-ER-40739, September1, 1992 - August 31, 1995.

II. ELECTROMAGNETICS

THE UNIVERSITY OF TEXAS AT AUSTIN   ELECTRONICS RESEARCH CENTER
                                          ELECTROMAGNETICS

Research Unit EM92-1:   MICROWAVE/MILLIMETER WAVE HYBRID MICROELECTRONIC
                         CIRCUITS

Principal Investigators: Professor D. P. Neikirk (471-4669)

Graduate Students: S. Javalagi, S. Islam, V. Reddy, A. Tsao

A. __SCIENTIFIC OBJECTIVES__: The objective of this unit is to conceive and develop novel circuit configurations and new solid state devices for microwave and millimeter-wave applications. These circuit structures are intended to provide an electromagnetic environment that maximizes the potential capability of the solid state devices grown using our Varian GEN II molecular beam epitaxy (MBE) facility, in conjunction with Unit SSE92-1. To further increase the flexibility and performance of our RF circuits, we are also investigating the use of the epitaxial lift-off (ELO) technique to allow the integration of compound semiconductor devices on alternative substrates.

B. __PROGRESS__: The effort during this reporting period is in the following areas: (1) development of planar process fabrication technology for high frequency measurements; (2) experimental characterization of extremely high breakdown voltage quantum barrier varactor frequency multiplier diodes; and (3), the use of the epitaxial lift-off technique for low -loss, high optical sensitivity (controlled by Light Emitting Diode) coplanar waveguide phase shifters. These subjects have a common goal of integrating high frequency sources in an appropriate circuit so that the electromagnetic interaction with active devices is effectively utilized in the development of millimeter wave components.

Planarized QWITT Diode Oscillators

During this period we have been developing a planarized diode fabrication process. The four level mask planar process utilizes an air-bridge technology for isolation between the bias pad and the ground plane. Accurate device impedance measurements using coplanar RF wafer probes will be possible with this device lay-out since large parasitic elements are minimized. Furthermore, spatial power combining approaches can be developed using this planarized device fabrication process.

We have recently obtained the masks and have developed a process flow. One of the process challenges is establishing a reliable, low resistance gold air-bridge technology. One early problem in this area was the lack of photoresist adhesion during the electroplating process. We have solved this problem by incorporating a thin layer of nickel to improve adhesion. By using this process innovation, we have achieved reliable gold air bridges. Work is underway to characterize the process by fabricating test structures and varying process parameters. Once the process is optimized, it can be used for fabricating high performance diode structures.

Quantum Barrier Varactor Diode Frequency Multipliers

In the past several years we have performed extensive simulations on t. ⌐ high frequency (200 GHz - 1 THz) performance of resonant tunneling diode oscillators. These simulations have shown that it is extremely difficult to obtain useful amounts of power (1 mW) from any resonant tunneling diode oscillator, including QWITT diodes. At such high frequencies current densities of over 150,000 A/cm^2 will be required. Even using QWITT design principles (which maximize available negative resistance), devices with areas large enough to produce even 0.1 mW will have extremely low impedances (< 1 Ω). At frequencies above 200 GHz it will be extraordinarily difficult to produce planar circuits with such low matching impedances. A more attractive approach is

frequency multiplication of a high power, lower frequency (< 100 GHz) source. The most common technique for solid state frequency multiplication is to use a Schottky varactor diode. Recently, Erickson reported a GaAs Schottky diode tripler that achieved 700 μW at 500 GHz with 3% tripler conversion efficiency [1]. Rydberg et al. obtained 120 μW and 0.8% conversion efficiency with a tripler to 803 GHz [2]. However, further improvements in Schottky diode technology are required for attaining useful powers at terahertz frequencies [3].

Towards this end, a new type of varactor, the quantum barrier varactor (QBV), has been developed by Kollberg et al. [4]. Since this device exhibits an even symmetry in its capacitance versus voltage (C-V) characteristic, only odd harmonics are generated during frequency multiplication. In contrast, a Schottky barrier varactor multiplier generates all higher order harmonics due to its asymmetric C-V characteristics. In the design of a quintupler using a QBV, for example, only an idler circuit at the third harmonic is required, thereby reducing circuit design and eliminating losses due to unoptimized idler terminations. Recently, Rydberg et al. and Gronqvist et al. have demonstrated QBV frequency triplers to 280 GHz with output powers and tripler conversion efficiencies of 1 - 2 mW and 5%, respectively [5,6]. These figures were similar to that obtained with a high performance Schottky diode tripler in the same tripler mount. However, the performance of these QBV devices were limited by excessive conduction current during operation. This parasitic conduction reduces multiplier efficiency since resistive multiplication is far less efficient than reactive multiplication [7]. The device design challenge, therefore, for high performance QBV operation is reducing conduction current during device operation while maintaining a large nonlinearity in the C-V characteristic and low parasitic series resistance. Reduction of this deleterious conduction will consequently improve the QBV's power handling capability and relax device and circuit design requirements.

To reduce leakage currents and improve the power handling capability of QBV diodes we have begun investigation of the AlAs / $In_{0.53}Ga_{0.47}As$ material system. This material system is very attractive for several reasons pertinent to QBV applications. The Γ-Γ band offset between AlAs and $In_{0.53}Ga_{0.47}As$ is 1.2 eV and the AlAs / $In_{0.53}Ga_{0.47}As$ Γ-X band offset is 0.65 eV [8]. The large Γ-Γ and Γ-X barrier heights should greatly reduce conduction current over that of the AlGaAs / GaAs material system [9]. Further, very low resistance non-alloyed ohmic contacts can be fabricated, an important requirement in reducing the diode's parasitic series resistance. Such contacts may also be more uniform over large wafers, an important requirement for monolithic grid array multipliers. This material system has been employed previously in fabricating very high peak-to-valley current ratio resonant tunneling diodes [10] and very high efficiency microwave oscillators [11].

The devices studied were grown by molecular beam epitaxy on n+ InP substrates at 500° C. Mesa isolated diodes with non-alloyed AuCr topside contacts were then fabricated with standard photolithographic techniques and wet chemical etching. The layer schematic of three QBV structures are shown in Fig. 1, where L denotes the thickness of the barrier layer, and BARRIER represents its composition. For the first device, QBV I, L = 50 Å and BARRIER = AlAs. The second device, QBV II, has L = 100 Å and BARRIER = AlAs. For the third structure, QBV III, L = 50 Å / 50 Å / 50 Å and BARRIER = $In_{0.52}Al_{0.48}As$ / AlAs / $In_{0.52}Al_{0.48}As$. The capacitance modulation is obtained through the depletion of the 3000 Å (1.2 x 10^{17} cm^{-3}) $In_{0.53}Ga_{0.47}As$ layers. The heavily doped (2.2 x 10^{19} cm^{-3}) $In_{0.53}Ga_{0.47}As$ top contact layer allows the formation of a low resistance non-alloyed ohmic contact.

The 300 K current density versus voltage (J-V) characteristics of the three structures are shown together in Fig. 2. Although the J-V characteristics are very symmetric, for clarity only one bias direction (positive voltage applied to top contact) is shown. All three diodes exhibit excellent current blocking characteristics with breakdown voltages between 10 V and 12 V. QBV II and QBV III have similar characteristics, with QBV III blocking slightly better at lower voltages. For low voltages (less than 5 volts) QBV II and III have current densities several orders of magnitude lower

than QBV I, which has the thinnest barrier. To our knowledge, these are the highest breakdown voltages reported for QBVs. Rydberg et al. reported an AlSb / InAs QBV with a 200 Å AlSb barrier and 4000 Å (6×10^{16} cm^{-3}) InAs depletion layers that had a current density of about 5 A cm^{-2} at 1 V [12]. In comparison, QBV III has a current density of only 4×10^{-4} A cm^{-2} at 1 V, not reaching a current density of 5 A cm^{-2} until 7 V. The C-V characteristics of the devices are shown in Fig. 3. As expected, the curves are symmetric about the voltage axis and the zero-bias capacitance increases as the barrier thickness decreases. The C_{max}/C_{min} ratio varies from 6 for QBV I to 4 for QBV III. Although very efficient current blocking has been achieved with single barrier structures, further improvements in power handling capability can be achieved by stacking several single barrier structures in series [13].

Coplanar Waveguide Phase Shifters

To further increase the flexibility and performance of our RF circuits, we have used the Epitaxial Lift Off (ELO) technique to fabricate a new, low-loss, LED-controlled coplanar waveguide (CPW) phase shifter. Schottky-contacted coplanar waveguide (CPW) on GaAs substrates have produced large phase shifts of microwave signals when the substrate is optically illuminated, even at very low illumination intensities [14]. The performance of these devices can be substantially improved by the use of ELO [15] where the original semi-insulating GaAs substrate is replaced by an optically transparent, low dielectric constant quartz substrate [16]. This allows illumination from the CPW back side, thus avoiding electrode shadowing and providing larger area for light absorption. Here we report the performance of optically-controlled phase shifters where the illumination source is a common plastic-encapsulated red LED.

The original CPW phase shifter substrate consists of an epitaxial layer of 3 µm thick lightly-doped n-type ($\sim 5 \times 10^{15}$ cm^{-3}) GaAs grown on a semi-insulating (SI) (100)-oriented GaAs wafer, with a 500 Å AlAs release layer sandwiched between the active layer and the substrate. CPW electrodes are then fabricated on the GaAs-AlAs-SI GaAs substrate combination. The CPW electrodes consist of 100 Å of evaporated chrome, 200 Å of evaporated gold, and 1 µm of electroplated gold. The center conductor of the CPW is 10 µm wide, and the gaps to the ground planes are 7 µm. To remove the epitaxial layer and CPW from the SI substrate the AlAs release layer is selectively etched away and the thin epitaxial layer is transferred onto a quartz substrate [3]. For these devices a cyanoacrylate adhesive was used to provide a robust, optically transparent bond between the GaAs epi-layer and the quartz substrate. Figure 4(a) shows a cross section of the completed device.

Maximum sensitivity to optical illumination is obtained when a dc reverse bias is applied to the CPW electrodes that just depletes the epitaxial layer under the metal at zero illumination intensity. At this dc bias very low levels of illumination induce large changes in the CPW transmission line admittance per unit length, which can be explained in terms of a distributed transverse resistance and capacitance model [17, 18]. For the doping concentration and the layer thickness used here, a reverse bias of 29 V applied to the ground plane conductors with respect to the center conductor produced maximum sensitivity. At this bias and at zero illumination intensity, the propagation constant and characteristic impedance of the CPW is approximately that of a CPW on a lossless substrate. The CPW phase shifter was illuminated with an inexpensive (present cost US $1 - $2) commercially available epoxy-encapsulated red LED ($\lambda = 0.6$ µm - 0.75 µm). The LED is placed just underneath the quartz substrate providing back side illumination of the GaAs, thus allowing higher light absorption in the active GaAs layer (Figure 1a). The LED used here can produce ~190 µW of optical power at a dc power level of 87 mW; this LED setting was the maximum optical power used to produce phase shift over a 20 - 40 GHz frequency range. The optically-induced phase shift and the insertion loss of a 1 cm long CPW were measured with an HP 8510B automatic network analyzer and wafer probes.

Based on the measured phase shift per centimeter at maximum illumination intensity, the length of a device designed to produce a 90° phase shift can be calculated, as shown in Figure 5. For such a 90° phase shifter, the optically induced phase shift and the insertion loss as a function of LED optical output power are shown in Figures 6 and 7, respectively. At 35 GHz, a 90° phase shifter would be about 3.5 mm long, with about 11 dB of insertion loss at 90° phase shift (for maximum LED illumination intensity), and about 4 dB of loss at 0° phase shift (for zero illumination intensity). The simple structure and the inexpensive optical source used here make this device a potential candidate for commercial application as a phase shifter. The very high optical sensitivity exhibited by the GaAs-on-quartz CPW is critical to the development of practical optically-controlled microwave components.

Using the ELO process it should also be possible to integrate a simple GaAs-AlGaAs double-heterojunction (D-H) LED with the phase shifter using both sides of the quartz substrate, as illustrated in Fig. 4(b). Design and fabrication of an ELO LED has already been performed. With direct bonding of the LED opposite the CPW phase shifter, much higher optical coupling efficiency should be realized. Such an integrated LED / phase shifter should require much lower dc drive power for the optical source, making the control of the device extremely simple.

C.   FOLLOW-UP STATEMENT: Application of our new air-bridge planarized fabrication process to QWITT diodes will begin as soon as the Microelectronics Research Center facilities have completed their move to their new location. We have also begun investigation of low temperature AlGaAs as a blocking layer in QBVs. Finally, an integrated LED/CPW pair will be fabricated for testing as a hybrid/monolithic phase shifter.

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I. LIST OF PUBLICATIONS (*JSEP Supported in whole or in part)

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K. K. Gullapalli, A. J. Tsao, and D. P. Neikirk, "Multiple self-consistent solutions at zero bias and multiple conduction curves in quantum tunneling diodes containing N^- - N^+ - N^- spacer layers," submitted for publication in **Appl. Phys. Lett.** , Aug. 1992.

K. K. Gullapalli, A. J. Tsao, and D. P. Neikirk, "Experimental observation of multiple current - voltage curves and zero-bias memory in quantum well diodes with N^- - N^+ - N^- spacer layers," submitted for publication in **Appl. Phys. Lett.** , Oct. 1992.

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* M. Saiful Islam, Emre Tuncer and Dean P. Neikirk, "Accurate Quasi-Static Model for Conductor Loss in Coplanar Waveguide," submitted to **Electronics Letters**, Jan. 8, 1993.

II.   LIST OF CONFERENCE PROCEEDINGS (*JSEP Supported in whole or in part)

* Douglas R. Miller and D.P. Neikirk, "Lattice Wigner simulations of double barrier resonant tunneling devices," Third International Symposium on Space Terahertz Technology, The University of Michigan, Ann Arbor, Mich., March 24-26, 1992, pp. 560-574.

Nanda Gopal, Emre Tuncer, Dean P. Neikirk, and Lawrence T. Pillage, "Non-uniform lumping models for transmission line analysis," IEEE Topical Meeting on Electrical Performance of Electronic Packaging, Tucson, AZ, April 22-24, 1992, pp. 119-121.

* K.K. Gullapalli and D.P. Neikirk, "Evaluating space charge resistance in resonant tunneling diodes," 11th Annual Symposium on Electronic Materials, Processing, and Characterization, Richardson, TX, June 1-2, 1992.

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* Alwin J. Tsao, M.S. Islam, and D.P. Neikirk, "Epitaxial liftoff of GaAs/AlGaAs thin film device structures for hybrid integration on silicon and quartz substrates," 11th Annual Symposium on Electronic Materials, Processing, and Characterization, Richardson, TX, June 1-2, 1992 (Best Student Paper Award).

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K.K. Gullapalli, A.J. Tsao, and D.P. Neikirk, "Observation of zero-bias multi-state behavior in selectively doped two-terminal quantum tunneling devices," 1992 IEEE International Electron Devices Meeting, San Francisco, CA, Dec. 13-16, 1992, pp. 479-482.

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III.   LIST OF PRESENTATIONS (*JSEP Supported in whole or in part)

* D. P. Neikirk and B.G. Streetman, "MBE growth of multilayer heterostructures for photonic and high-speed electronic devices," Engineering Foundation Conference on High Speed Optoelectronic Devices and Circuits II, Banff, Alberta, Canada, Aug. 9-13, 1992.

T.R. Block, D.P. Neikirk, and B.G. Streetman, "MBE growth condition dependence of RHEED dampening and QW photoluminescence," Twelfth North American Conference on Molecular Beam Epitaxy, Ottawa, Canada, Oct. 12-14, 1992.

T.J. Mattord, D.P. Neikirk, A. Srinivasan, A. Tang, K. Sadra, Y.C. Shih, and B.G. Streetman, "Real time flux monitoring and feedback control of a valved arsenic source" Twelfth North American Conference on Molecular Beam Epitaxy, Ottawa, Canada, Oct. 12-14, 1992.

Y.C. Shih, D.P. Neikirk, and B.G. Streetman, "Effects of As flux on Si d-doped GaAs," Twelfth North American Conference on Molecular Beam Epitaxy, Ottawa, Canada, Oct. 12-14, 1992.

IV.   GRANTS AND CONTRACTS

IBM Corp., "IBM Faculty Development Award," Professor D. P. Neikirk, Principal Investigator.

National Science Foundation, "Presidential Young Investigator Award," Professor D. P. Neikirk, Principal Investigator.

Texas Advanced Technology Program, "Quantum Well Device-based Circuits for Millimeter Wave Communications Applications," Professors D. P. Neikirk and T. Itoh, Co-Principal Investigators.

Texas Advanced Research Program, "Quantum Transport Models for Heterostructure Devices," Professor D. P. Neikirk, Principal Investigator.

Defense Advanced Research Projects Agency, "Journal and Thrust Bearings with Active Deformable Surfaces," Professors I. Busch-Vishniac, D.P. Neikirk, W. Weldon, and K. Wood, Co-Principal Investigators.

2000Å	n+ $(2.2 \times 10^{19} cm^{-3})$	InGaAs
3000Å	n- $(1.2 \times 10^{17} cm^{-3})$	InGaAs
50Å	UNDOPED	InGaAs
L	UNDOPED	BARRIER
50Å	UNDOPED	InGaAs
3000Å	n- $(1.2 \times 10^{17} cm^{-3})$	InGaAs
2000Å	n+ $(2.2 \times 10^{19} cm^{-3})$	InGaAs
	n+ InP	Substrate

Figure 1 The layer schematic of the three QBV structures studied where L denotes the thickness of the barrier layer and BARRIER represents its composition. QBV I (L = 50Å and BARRIER = AlAs); QBV II (L = 100Å and BARRIER = AlAs); QBV III (L = 50Å/50Å/50Å and BARRIER = $In_{0.52}Al_{0.48}As/AlAs/In_{0.52}Al_{0.48}As$).
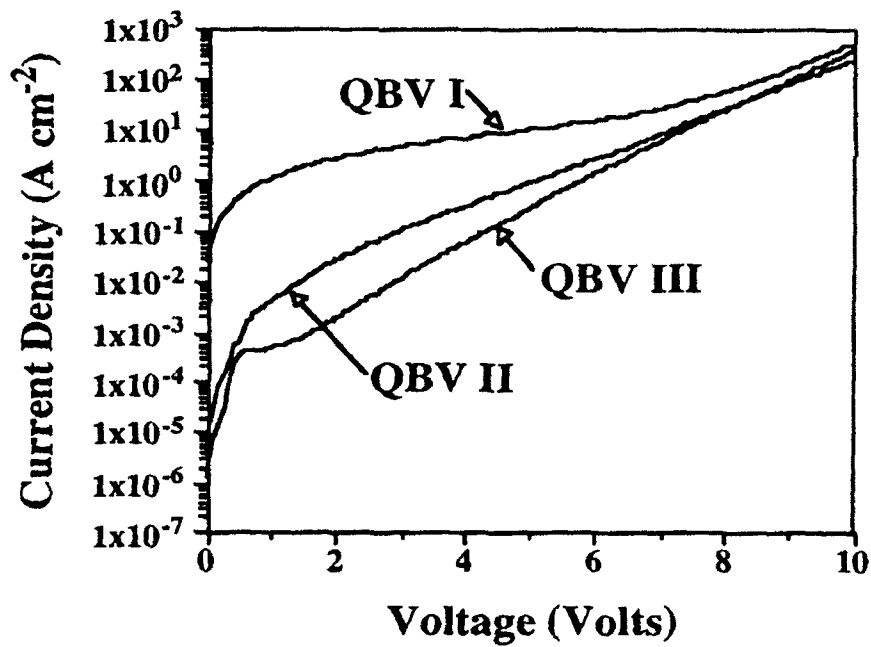
Figure 2 Current Density versus Voltage characteristics at 300K for the three device structures. The device areas ranged from 470 μm^2 to 530 μm^2.
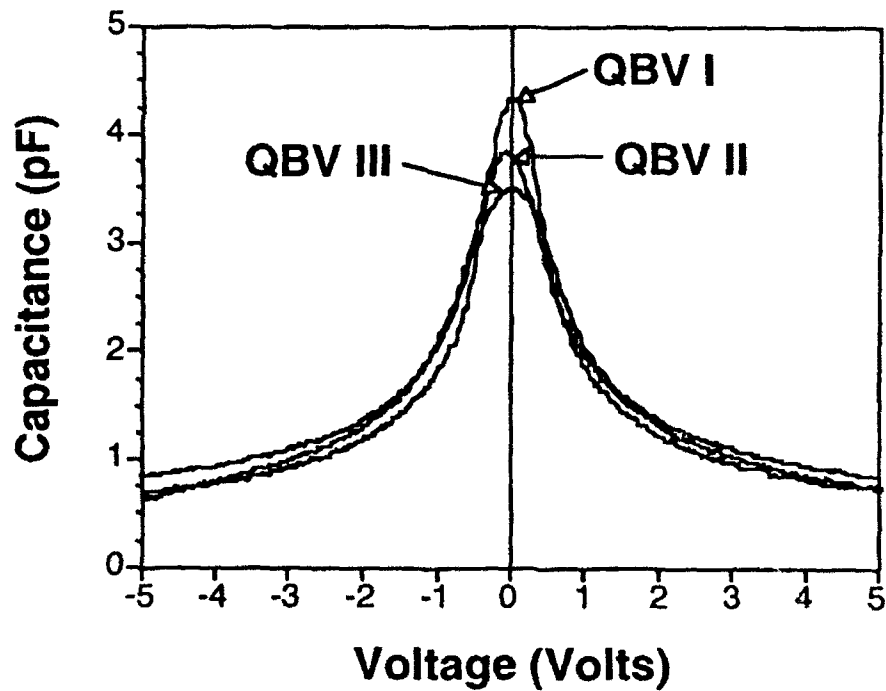
Figure 3 Capacitance versus voltage characteristics at 300K. The measurement frequency is 1 MHz. Device area is approx. 2025 μm^2.
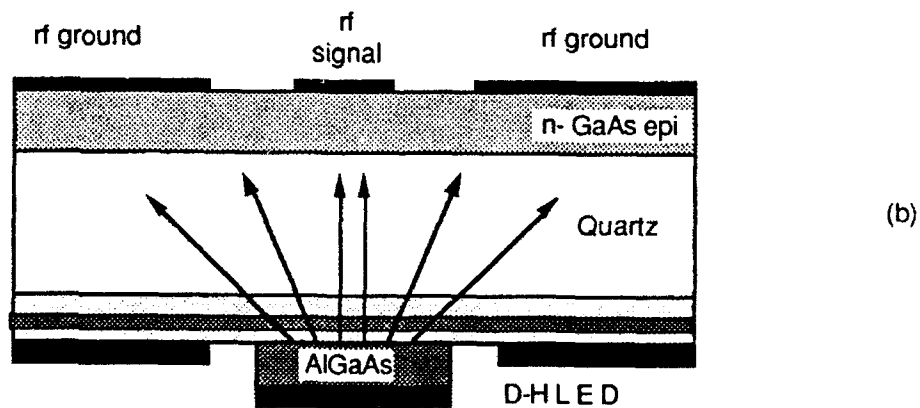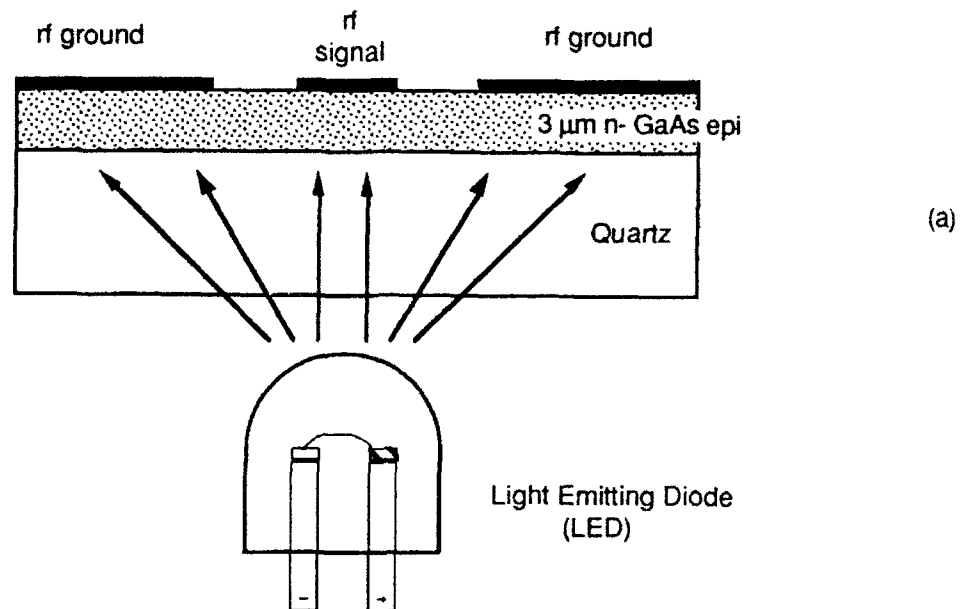
Figure 4: Cross-section of an optically-controlled CPW phase shifter on a GaAs-on-quartz substrate. (a) Configuration of commercially available LED illumination source; (b) Integrated double-heterojunction (D-H) LED/CPW pair using the epitaxial lift-off technique to bond AlGaAs/GaAs layers to both sides of the quartz substrate.

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Figure 5: CPW transmission line length required for a 90° phase shifter, found from phase shift measurements in a 1 cm long device, using a maximum illumination power from the red LED of about 200 μW.

Figure 6: Phase shift for a 90° phase shifter as a function of LED illumination power.

Figure 7: Insertion loss of a 90° phase shifter as a function of LED illumination power.

Research Unit EM92-2:   Electromagnetic Scattering from Gaps, Cracks, Joints and Cavities

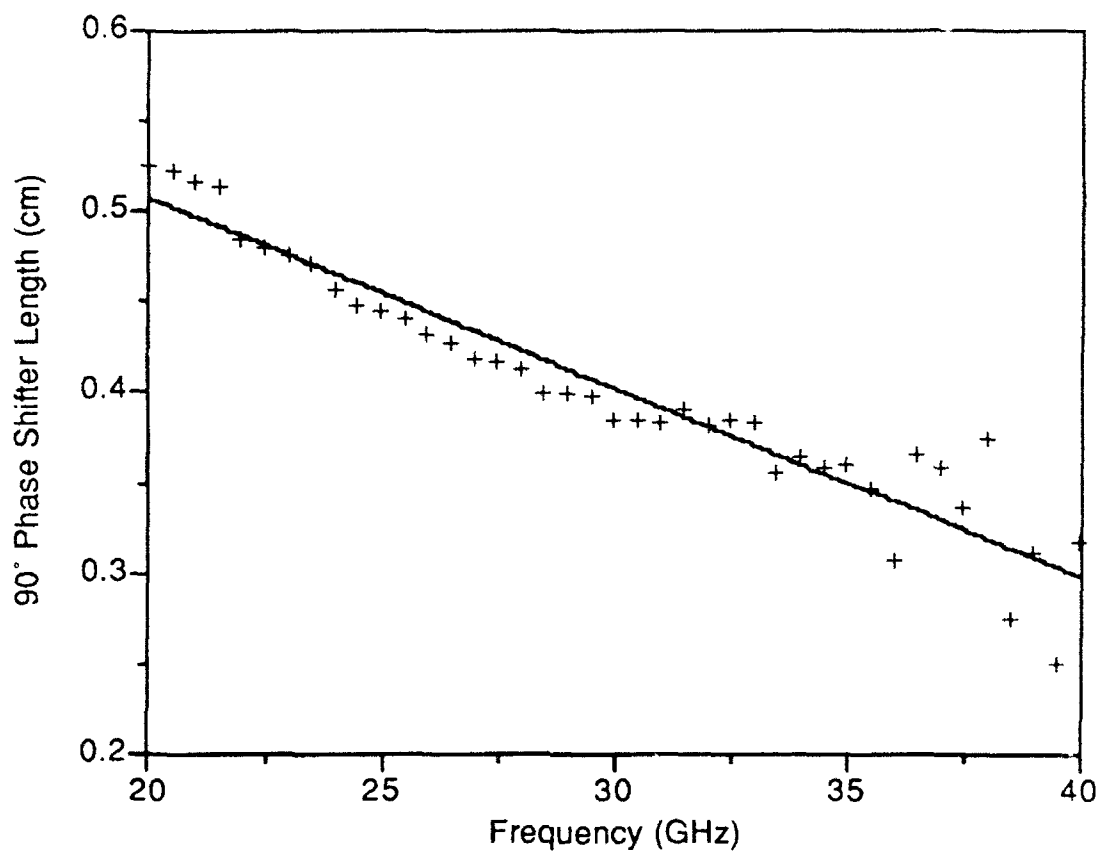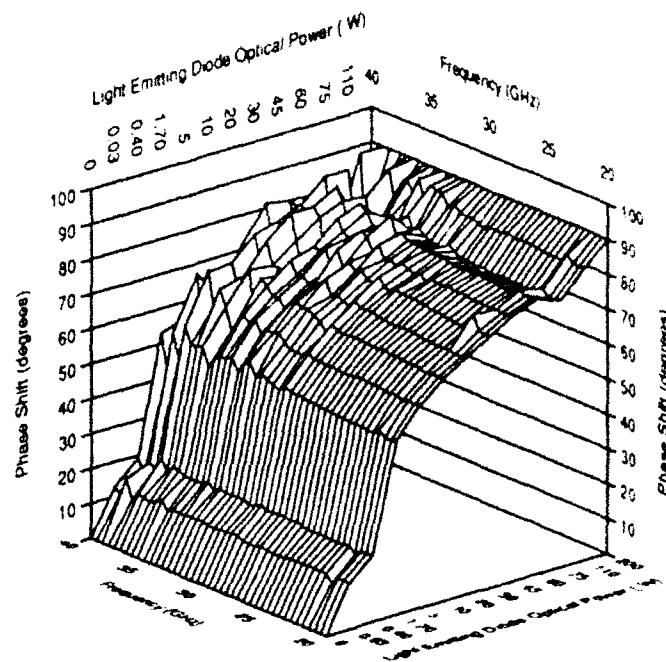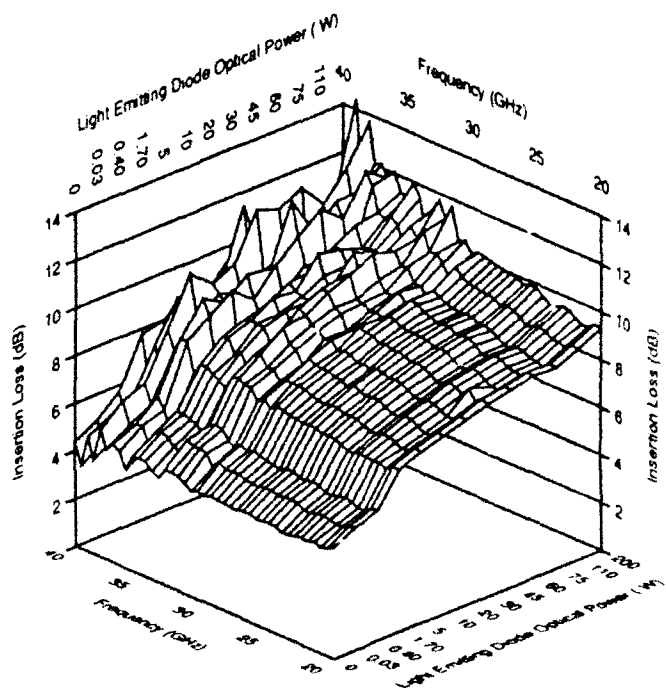Principal Investigator: Professor Hao Ling   (512) 471-1710

Graduate Students: J. Moore and R. Bhalla

A.   SCIENTIFIC OBJECTIVES: The objective of this research is to study the electromagnetic scattering from gaps, cracks, material joints and inlet cavities embedded in complex low-observable targets. It is well recognized by the radar cross section community that the scattering from sub-skinline features such as inlet ducts, on-board antennas and skinline seams can often be the dominant contributor to the overall radar signature of a complex target. We are ad 'ressing this research from two points of view. First, we are developing analysis methodologies based on numerical, asymptotic and hybrid techniques to accurately characterize the scattering features of this class of structures. The computational tools we develop will enable us to investigate the detailed scattering physics in these structures and the roles they play in the overall radar signature of low-observable targets. Second, we are implementing signal analysis schemes to analyze the backscattered data from structures containing sub-skinline features. The feature space representation of the backscattered signal will allow us to interpret and correlate the various signal constituents with the scattering phenomenology of the target for possible target identification applications.

B.   PROGRESS: During the first year of this research, we have focused our efforts in two specific areas. In computational electromagnetics research, we have developed a hybrid numerical-asymptotic method to tackle the problem of scattering from discontinuities embedded in composite materials and coated surfaces. This technique allows us to study the complex surface wave mechanisms in coated structure through a systematic building block approach. In the area of backscattered signal analysis, we have investigated the time-frequency representation of backscattered data from various targets such as inlet ducts and coated discontinuities. Both the conventional short-time Fourier transform and the more recently developed wavelet transform have been studied as a means of generating the time-frequency representation. Our detailed progress is described below.

In refs. [5, 10], we present a method for extracting the numerical diffraction coefficients of coated edges and material gaps. An exact boundary integral formulation is used without resorting to the impedance boundary condition approximation. To handle the semi-infinite problem numerically, the non-decaying physical optics (PO) and surface wave fields are removed from the boundary integral equation such that the final discretization domain involves only a finite region near the edge. Numerical diffraction coefficients and surface wave launch coefficients are extracted based on the Uniform Theory of Diffraction (UTD) framework. Solutions to several finite sized coated structures are constructed using this numerical UTD (NUTD) approach and are shown to be valid for a wide range of coatings. Furthermore, surface wave interactions are shown to be a significant contributor to the overall backscattering. This approach can also be easily extended to study related structures such as material joints. Most importantly, the building block approach of the NUTD provides an attractive means of studying the complex scattering physics occurring in coated structures.

In ref. [11], we extend our study to material coated two-dimensional periodic surfaces under oblique incidence. The boundary integral method is used to characterize the complex contour of a single groove of the grating. The underlying periodicity of the infinite structure is accounted for by applying periodic boundary conditions and expanding the fields in terms of Floquet harmonics.

For conducting gratings, the numerical results of this method are in good agreement with measured data at 30 THz for an infrared grating fabricated on silicon substrate [4, 8]. This validation effort was carried out in collaboration with our colleagues in the Astronomy Department. For coated surfaces, our numerical results indicate a strong coupling between polarizations that results from oblique incidence. We find that the groove profile could be used in conjunction with a lossy dielectric material to improve the absorbing characteristics of surfaces for both polarizations. We are now pursuing this novel absorber idea in collaboration with General Dynamics.

We have started a parallel effort in the area of backscattered data analysis, with particular emphasis on sub-skinline feature extraction. Target characteristics are commonly extracted in practice by analyzing the backscattered signal in either the time or the frequency domain. For example, the natural resonances of a target are manifested in the frequency domain as sharp, discrete events and can be attributed to the unique global features of the target. Similarly, scattering centers are manifested in the time domain as distinct time pulses and can be related to the local features on the target. For dispersive phenomena, however, the scattering characteristics are not apparent in either the time or the frequency domain. They are best characterized in the joint time-frequency domain. Since most sub-skinline features contain dispersive scattering mechanisms such as surface waves and leaky interior modes, time-frequency analysis is ideally suited for this purpose. In ref. [9], the short-time Fourier transform is applied to analyze the backscattered signal from a coated strip with a narrow gap in the coating. The backscattered data is generated by numerical simulation as well as measurements carried out by our colleagues from CESTA, France. The resulting time-frequency display shows good localization of the different scattering mechanisms. In particular, the time-frequency analysis is superior to the time domain or frequency domain analysis in identifying the dispersive surface wave contributions. In addition, the different scattering mechanisms can be extracted using a time-frequency gating idea. This is a natural extension of the time-gating concept and allows the original signal in either the time domain or the frequency domain to be decomposed into a set of fundamental scattering mechanisms.

We have also applied the more recently introduced wavelet analysis technique to backscattered signal analysis. Since the frequency-domain radar echo consists of both small-scale natural resonances and large-scale scattering center information, the multi-resolution property of the wavelet transform is well suited for analyzing such multi-scale signals. Wavelet analysis examples of backscattered data from an open-ended waveguide cavity and a plasma cylinder are presented in refs. [1, 2, 6]. Compared to the conventional short-time Fourier transform, the wavelet transform provides a more efficient representation of both the early-time scattering center data and the late-time resonances. Moreover, since the wavelet transform representation in the time-frequency plane is sparse, it may also be useful for the compression of backscattered data. By using the discrete wavelet transform, the amount of data that needs to be stored in the time-frequency plane may be significantly less than that in either the time or the frequency domain. This can be accomplished by keeping all wavelet coefficients larger than some threshold and setting all smaller coefficients to zero. With a small number of wavelet coefficients that have been kept, the original frequency-domain or time-domain data can be reconstructed without loss of fidelity. The compression of the backscattered data and the feasibility of extracting feature vectors for target identification algorithms will be areas of our future investigation.

Finally, we have attempted to apply the fast wavelet transform to the integral equation solution of two-dimensional computational electromagnetics problems [7]. In the wavelet transform domain, the moment method impedance matrix becomes sparse and sparse matrix algorithms can be utilized to solve the resulting matrix equation. Using the fast wavelet transform in conjunction with the conjugate gradient method, we study the time performance for the solution of a dihedral corner reflector. By thresholding the small elements of the impedance matrix in the wavelet domain, it is found that the total computation complexity could be reduced without sacrificing much accuracy in the solution for the induced current. The sparsity of impedance matrices in the

moment method is investigated and problems with using the existing wavelets for oscillatory kernels are pinpointed. From this study, we conclude that a more specialized set of wavelet basis is needed to efficiently represent oscillatory kernels encountered in electrodynamic problems.

C. FOLLOW-UP STATEMENT: This work is continuing along the two focused areas. First, we will continue the development of prediction methodologies for the characterization of gaps, cracks, material joints and inlet cavities. Second, we will explore additional signal analysis schemes to understand and extract scattering phenomenology from sub-skinline features. We will also further investigate the applicability of wavelet theory in electromagnetics.

I. List of Journal Publications

1. * H. Kim and H. Ling, "Wavelet analysis of electromagnetic backscatter data," **Elect. Lett.**, vol. 3, pp. 279-281, January 1992.

2. * H. Ling and H. Kim, "Wavelet analysis of backscattering data from an open-ended waveguide cavity," **IEEE Microwave and Guided Wave Letters**, vol. 2, pp. 140-142, April 1992.

3. H. Kim and H. Ling, "Electromagnetic scattering from an inhomogeneous body by ray tracing," **IEEE Trans. Antennas Propagat.**, vol. AP-40, pp. 517-525, May 1992.

4. * J. Moore, H. Ling, U. U. Graf and D. T. Jaffe, "A boundary integral approach to the scattering from periodic gratings," **Microwave Optical Tech. Lett.**, vol. 5, pp. 480-483, September 1992.

5. * J. Moore and H. Ling, "Scattering by gaps in coated structures," **J. Electromag. Waves Applications**, accepted for publication and in press.

6. * H. Kim and H. Ling, "Wavelet analysis of radar echo from finite-size targets," **IEEE Trans. Antennas Propagat.**, accepted for publication and in press.

7. * H. Kim and H. Ling, "On the application of fast wavelet transform to the integral equation solution of electromagnetic scattering problems," **Microwave Optical Tech. Lett.**, accepted for publication and in press.

8. U. U. Graf, D. T. Jaffe, E. J. Kim, J. H. Lacy, H. Ling, J. T. Moore and G. Rebeiz, "Fabrication and evaluation of an etched infrared diffraction grating," submitted to **Appl. Opt.**

9. * H. Ling, J. Moore, D. Bouche and V. Saavedra, "Time-frequency analysis of backscattered data from a coated strip with a gap," submitted to **IEEE Trans. Antennas Propagat.**

10.* J. Moore and H. Ling, "Boundary integral solution to the diffraction and surface wave mechanisms in the coated edge," submitted to **J. Electromag.Waves Applications**.

11.* J. Moore, H. Ling and C. S. Liang, "The scattering and absorption characteristics of material coated periodic gratings under oblique incidence," submitted to **IEEE Trans. Antennas Propagat.**

12.* R. Bhalla and H. Ling, "ISAR image formation using bistatic data computed from the shooting and bouncing ray technique," submitted to **J. Electromag. Waves Applications**.

II.   List of Conference Proceedings

13.   U. U. Graf, D. T. Jaffe, E. J. Kim, J. H. Lacy, H. Ling, J. T. Moore and G. Rebeiz, "Fabrication and evaluation of an etched infrared diffraction grating," Astronomical Infrared Spectroscopy Conference, Calgary, Canada, June 1992.

14.*   H. Kim and H. Ling, "Analysis of electromagnetic backscattering data using wavelets," International IEEE AP-S Symposium, pp. 1877-1880, Chicago, IL, July 1992.

15.*   J. Moore and H. Ling, "Numerical diffraction coefficients for the conductor-backed dielectric half-plane," International IEEE AP-S Symposium, pp. 305-308, Chicago, IL, July 1992.

16.   M. Zimmerman, S. W. Lee, B. Houshmand and H. Ling, "Solar exploration initiative multibeam antenna study," International IEEE AP-S Symposium, pp. 1359-1362, Chicago, IL, July 1992.

17.*   H. Ling, J. Moore, D. Bouche and V. Saavedra, "Time-frequency analysis of backscattered data from a coated strip with a gap," National Radio Science Meeting, p. 195, Boulder, CO, January 1993.

18.*   J. Moore and H. Ling, "Scattering by gaps in coated strips," National Radio Science Meeting, p. 173, Boulder, CO, January 1993 (2nd Place, Student Paper Competition).

19.*   J. Moore, H. Ling and C. S. Liang, "Boundary integral solution to scattering from coated grooves at oblique incidence," National Radio Science Meeting, p. 172, Boulder, CO, January 1993.

20.   W. J. Vogel, H. Ling and G. W. Torrence, "Modulated multipath propagation effects for personal communication in the office environment," National Radio Science Meeting, p. 153, Boulder, CO, January 1993.

21.   H. Ling and H. Kim, "A ray based approach to scattering from inhomogeneous dielectric objects," to be presented at the 9th Annual Review of Progress in Applied Computational Electromagnetics, Monterey, CA, March 1993 (Invited Paper).

22.*   R. Bhalla and H. Ling, "ISAR image formation using bistatic data from XPATCH," to be presented at the 9th Annual Review of Progress in Applied Computational Electromagnetics, Monterey, CA, March 1993.

23.*   J. Moore, H. Ling and C. S. Liang, "Scattering by lossy material coated periodic gratings under oblique incidence," submitted for presentation at the 1993 International IEEE AP-S Symposium, Ann Arbor, MI, June 1993.

24.*   H. Kim and H. Ling, "Modal propagation algorithm for RCS prediction of inlet ducts," submitted for presentation at the 1993 International IEEE AP-S Symposium, Ann Arbor, MI, June 1993.

25.*   L. C. Trintinalia, H. Ling and T. M. Wang, "Electromagnetic scattering from 3-D treated cavities via a connection scheme using triangular surface patches," submitted for presentation at the 1993 URSI Radio Science Meeting, Ann Arbor, MI, June 1993.

III.   List of Related Presentations

26.   "Electromagnetic scattering from corrugated surfaces," General Dynamics Corp., Fort Worth, Texas, July 2, 1992.

27.   "ARTI Research at the University of Texas," ARTI Synthesis Meeting, Wright-Patterson Air Force Base, Dayton, Ohio, July 10, 1992.

28.* "Electromagnetic scattering from gaps, cracks, joints and cavities," Microwave Seminar, Texas A&M University, College Station, Texas, December 1, 1992.

29.   "Simulating monostatic data using bistatic data," ARTI Synthesis Meeting, Wright-Patterson Air Force Base, Dayton, Ohio, January 15, 1993.

IV.   List of Theses and Dissertations

   Ph.D.

   H. Kim, "Interaction of microwave signal with an arcjet plasma plume," May 1992.

   J. Moore, "Boundary integral solution to the electromagnetic scattering from coated surfaces containing edges, gaps and periodic gratings," December 1992.

V.   Contracts and Grants

   H. Ling, "Toward the realistic modeling of electromagnetic scattering problems," Presidential Young Investigator Award, National Science Foundation, September 1, 1987 - June 30, 1993.

   H. Ling, "Scattering by conductor-backed dielectric gaps," Air Force Rome Laboratory (via Joint Services Electronics Program), July 1, 1991 - May 15, 1995.

   H. Ling, "Scattering from corrugated surfaces," General Dynamics Fort Worth Division, April 23, 1992 - December 31, 1992.

   H. Ling, "Electromagnetic scattering from cavities via a connection scheme," General Dynamics Fort Worth Division, April 29, 1992 - December 31, 1992.

   H. Ling, "Advanced studies of electromagnetic scattering," Wright-Patterson Air Force Base (via NASA Lewis Research Center), July 1, 1992 - April 15, 1994.

III. INFORMATION ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN   ELECTRONICS RESEARCH CENTER
                                          INFORMATION ELECTRONICS

Research Unit IE 92-1:   Multisensor Signal Processing

Principal Investigator: J. K. Aggarwal   (512)471-1369

Graduate Students: Sunil Gupta, Xavier Lebegue, H. Q. Lu, Bikash Sabata,
                           Rajendra Talluri

A.   **SCIENTIFIC OBJECTIVES**: The overall scientific objective of this research unit is to develop algorithms for analyzing signals from multiple sensors and multiple views. The objectives include the development of computer methods for the concomitant analysis of noisy information from several sensors and views, efficient techniques for signal processing and interpretation, and modeling signal uncertainties based on physical principles of signal generation, detection and interactions. Information from different sources may then be optimally combined using statistical methods and artificial intelligence (AI) techniques.

The sensors used in the system include visual, infrared, laser radar and millimeter wave radar sensors. Rule-based methods can better implement the integration task among signal systems that do not have well-understood mathematical models Statistical analysis of signal generation and detection will be thoroughly investigated to model signal uncertainties for different sensors. Thus, the temporal integration of sensor information may be based on the Kalman filtering algorithm. In general, signal processing that integrates multisensory and multi-view data can provide information that cannot be obtained by processing the data individually. By integrating information from different sensors and from different views, a more powerful and robust system may be built to interpret the scenes of interest.

We are addressing a number of issues towards the implementation of a multi-sensor/multi-view system. To synergistically integrate information from different sensors and from different views, the most important issue is to model signal uncertainties for different modalities. The many differences between the principles of how these sensor devices work require that individual sensor systems be analyzed, and accurate models be established for sensed signals. The strategies to combine the extracted information and to interpret it in a consistent way are critical to multi-sensor signal processing.

B.   **PROGRESS**: We have conducted a significant amount of research in the analysis and interpretation of multisensor signals from both similar and diverse sensors, which are analyzed concomitantly to provide useful information regarding the sensed scene and its characteristics. A brief discussion of the approaches adopted and results for robust interpretation of sensed signals is presented below.

Applying Perceptual Organization to the Detection of Man-made Objects in Non-urban Scenes. Using the principles of perceptual organization, we have developed a new approach to the detection of man-made objects in a single, monochrome image of an outdoor, non-urban scene in which the man-made objects are unspecified and their appearance is unpredictable [1]. Our approach identifies and makes use of the prominent features that distinguish man-made objects from natural objects. Using techniques such as feature extraction, primitive structure formation, and segmentation, we hierarchically group low-level image features into a *region-of-interest*, an area which is deemed mostly likely to enclose man-made objects or a substantial part of a man-made object. Experimental results are presented using real images that include different man-made objects in complex backgrounds as well as a natural scene that contains no man-made

objects. Our results show that the located regions-of-interest properly enclose the man-made objects in the scenes.

Image Interpretation Using Multiple Sensing Modalities. This research develops methodology for an automatic interpretation system using multiple sensors (AIMS) [2]. Using registered laser radar and thermal images, the system's overall objective is to detect and recognize man-made objects at kilometer range in outdoor scenes. We apply the multisensor fusion approach to four sensing modalities---range, intensity, velocity, and thermal--to improve image segmentation and interpretation. Low-level attributes of image segments (regions) are computed by the segmentation modules and converted to KEE format. The knowledge-based interpretation modules are constructed using KEE and Lisp. AIMS applies forward chaining in a bottom-up fashion to derive object-level interpretations from databases generated by the low-level processing modules. Segments are grouped into objects, which are then classified into predefined categories using selected features. The efficiency of the interpretation process is enhanced by transferring non-symbolic processing tasks to a concurrent service manager program. A parallel implementation of the interpretation module on an MIMD machine is also reported. Experimental results using real data are presented and discussed.

Correspondence of Surfaces in a Sequence of Range Images for Motion Estimation and Tracking. A fundamental issue in motion estimation and tracking an object over a sequence of images is establishing correspondence between object features in different images of the sequence. For range image sequences, this problem translates into finding a match between the surface segments in pairs of range images. We have developed a new procedure for finding correspondence between surface segments in a series of real range images [3]. A graph search procedure forms the basis for the algorithm that computers the correspondence between surfaces. The solution uses geometrical and topological information derived from the scenes to direct the search procedure. The two scenes are modeled as hypergraphs, which are then matched using a sub-graph isomorphism algorithm. The hierarchical representation of the hypergraphs reduces the search space significantly and facilitates the encoding of the geometrical and topological information. We demonstrate the algorithm on different types of real range image sequences. The algorithm proves to be robust and performs extremely well in the presence of occlusions and incorrect segmentation results.

C. **FOLLOW-UP STATEMENT**: Past research and the on-going research conducted by this unit in the analysis and processing of signals from different sensors has demonstrated and documented that multisensor fusion is a powerful approach for signal processing and interpretation. We are continuing our efforts in signal modeling based on physical principles and field observations. We believe that continued effort will lead to the design of a robust signal analysis and interpretation system that exploits multiple information sources.

D. **REFERENCES**:

[1]   Lu, H. Q., and J. K. Aggarwal, "Applying Perceptual Organization to Detection of Man-made Objects in Non-Urban Scenes," *Pattern Recognition*, pp. 835-853, 1992.

[2]   Chu, C. C. and J. K. Aggarwal, "Image Interpretation Using Multiple Sensing Modalities," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, pp. 840-846, 1992.

[3]   Sabata, B. and J. K. Aggarwal, "Correspondence of Surfaces in a Sequence of Range Images for Motion Estimation and Tracking," *Proc. IAPR Workshop on Machine Vision Applications* (MVA-92), December 7-9, 1992, Tokyo, pp. 385-388.

E.   PUBLICATIONS, PRESENTATIONS, THESES AND DISSERTATIONS, AND GRANTS
     AND CONTRACTS.

I.   RELATED JOURNAL PUBLICATIONS (Papers supported by JSEP are marked with "*".)

1.   (*) Chu, C. C. and J. K. Aggarwal, "Image Interpretation Using Multiple Sensing Modalities,"
     IEEE Transactions on Pattern Analysis and Machine Intelligence, pp. 840-846, 1992.

2.   (*) Lu, H. Q., and J. K. Aggarwal, ' .Applying Perceptual Organization to Detection of Man-
     made Objects in Non-Urban Scenes," *Pattern Recognition*, pp. 835-853, 1992.

3.   Talluri, R. and J. K. Aggarwal, **"Position Estimation for an Autonomous Mobile
     Robot In an Outdoor Environment**," *IEEE Trans. on Robotics and Automation*, Vol.
     8, No. 5, pp. 573-584, 1992.

4.   Talluri, R. and J. K. Aggarwal, **"Image/Map Correspondence for Mobile Robot
     Self-location Using Computer Graphics**," to appear in *IEEE Transactions on
     Pattern Analysis and Machine Intelligence*, Special Issue on 3D Modeling in Image Analysis
     And Synthesis.

5.   Chang, Y. L., X. Lebègue and J. K. Aggarwal, **"Calibrating a Mobile Camera's
     Parameters**," *Pattern Recognition*, in press.

II. RELATED CONFERENCE PROCEEDINGS. (Papers supported by JSEP are marked with
     "*".)

1.   (*) Lebègue, X. and J. K. Aggarwal, **"Detecting 3-D Parallel Lines for Perceptual
     Organization**," *Proceedings of the Second European Conference on Computer Vision*,
     May 1992, pp. 720-724.

2.   (*) Lebègue, X. and J. K. Aggarwal, **"Extraction and Interpretation of
     Semantically Significant Line Segments for a Mobile Robot**," *Proceedings of
     the IEEE International Conference on Robotics and Automation*, Nice, France, May 1992,
     pp. 1778-1785.

3.   (*) Lebègue, X. and J. K. Aggarwal, "A Mobile Robot for Visual Measurements in
     Architectural Applications," *Proc. IAPR Workshop on Machine Vision Applications* (MVA-
     92), December 7-9, 1992, Tokyo, pp. 195-198.

4.   (*) Sabata, B. and J. K. Aggarwal, "Correspondence of Surfaces in a Sequence of Range
     Images for Motion Estimation and Tracking," *Proc. IAPR Workshop on Machine Vision
     Applications* (MVA-92), December 7-9, 1992, Tokyo, pp. 385-388.

5.   (*) Talluri, R. and J. K. Aggarwal, "Transform Clustering for Model-Image Feature
     Correspondence, *Proc. IAPR Workshop on Machine Vision Applications* (MVA-92),
     December 7-9, 1992, Tokyo, pp. 579-582.

6.   (*) Lebègue, X and J. K. Aggarwal, "ROBOTEX: An Autonomous Mobile Robot for Precise
     Surveying," International Conference on Intelligent Autonomous Systems (IAS-3),
     February 15-19, 1993, accepted for presentation.

7. (*) Talluri, R. and J. K. Aggarwal, "Autonomous Navigation in Cluttered Outdoor Environments using Geometric Visibility Constraints," International Conference on Intelligent Autonomous Systems (IAS-3), February 15-19, 1993, accepted for presentation.

8. Dhond, U. and J. K. Aggarwal, **"Analysis of the Stereo Correspondence Process in Scenes with Narrow Occluding Objects,"** *Proceedings of the 11th International Conference on Pattern Recognition,* The Hague, The Netherlands, August 30 - September 3, 1992, Vol. I, pp. 470-473.

9. Dhond, U. and J. K. Aggarwal, **"Computing Stereo Correspondences in the Presence of Narrow Occluding Objects,"** *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition,* Champaign, Illinois, 1992, pp. 758-764.

III. Related Presentations.

1. (*) X. Lebègue and J. K. Aggarwal, **"Semantically Significant Line Segments for a Mobile Robot--ROBOTEX,"** *Video Proceedings of the IEEE International Conference on Robotics and Automation,* Nice, France, May 1992 (Videotape presentation).

2. "Computer Vision at The University of Texas at Austin," Siemens Research Corp., Princeton, NJ, July 6, 1992.

3. "Vision on Robotics," Research briefing for representatives of Austin industry and various state and federal agencies, May 6, 1992.

IV. List of JSEP Supported Theses and Dissertations

None during this reporting term.

V. List of Grants or Contracts.

Army Research Office Contract DAAL-03-91-G-0050, "Fusion of Multiple Sensing Modalities for Machine Vision," J. K. Aggarwal, Principal Investigator (1991-1994)

Research Unit IE92-2:   Higher-Order Statistical Signal Processing
                             and Applications to Nonlinear Phenomena

Principal Investigator: Professor Edward J. Powers (512) 471-3954

Graduate Student: S.B. Im   Research Associate: S.B. Kim (part-time)

A.   SCIENTIFIC OBJECTIVES: The overall scientific objective of this research unit is to further develop
and apply digital signal processing techniques, based on higher-order statistics and Volterra system
theory, in the analysis and interpretation of actual data from nonlinear physical systems and in the
modeling of such systems and associated nonlinear phenomena. The proposed objective may be further
subdivided into the following topical areas:

Nonlinear System Identification Via Higher-Order Statistical Signal Processing: Here the objective is to
determine frequency- and/or time-domain Volterra kernels up to third (i.e. cubic) order, given the time
series of random input-output data. Since the Volterra model is used to model nonlinearities in many
areas of science and engineering, the ability to determine the Volterra kernels is of fundamental
importance. For example, knowledge of the Volterra kernels enables one to quantify the relative degrees
of linearity and nonlinearity as a function of frequency. Furthermore, such knowledge enables one to
quantify the nonlinear spectral energy transfer that occurs as a result of nonlinear wave (i.e., frequency
and/or wavenumber) interactions.

Most prior work in this area assumed that the random excitation of the nonlinear system was Gaussian.
This leads to tremendous mathematical simplification. Unfortunately, however, many "real world"
excitations are not sufficiently Gaussian to make use of this assumption. In fact, if one assumes the
random excitation is Gaussian, when in fact it is not, one will get erroneous estimates of the Volterra
kernels. This is because the effective nonlinearities associated with the nonGaussian signal will be
lumped in with the nonlinearities of the system under test. For this reason, one of our main objectives has
been focused on developing higher-order statistical signal processing algorithms to estimate Volterra
kernels for nonGaussian (as well as Gaussian) excitation. One drawback of such models are that they are
nonorthogonal, which, when using such models to "predict" the response power spectrum of a nonlinear
system, causes interference terms to be introduced. This greatly complicates the decomposition of the
observed response into its linear, quadratic, and cubic components. Thus, a second objective of our
current work is to eliminate these interference terms through the use of conditioned higher-order input
spectra which results in an orthogonal model.

Extension of our Volterra modeling capabilities to third-order (i.e., cubic systems) and taking into account
the possible nonGaussian nature of the excitation requires that the statistics of the excitation be
characterized up to sixth-order. To make "good" estimates of such sixth-order spectral moments requires
a relatively large amount of raw experimental data (compared to the amount required for classical spectral
analysis of linear systems). Unfortunately, in some cases it may be prohibitively expensive to obtain the
large amounts of data required (e.g., wind tunnel, wave basin, flight tests); thus, our third objective is to
seek ways of reducing the amount of required raw data without significantly reducing the quality of the
kernel estimators.

Another related issue involves computational complexity and associated computational costs of the
algorithm used to estimate the kernels. For this reason an additional objective is to investigate the
possibility of reducing computational complexity for certain special cases of excitation signals such as i.i.d.
inputs.

Applications: As is mentioned at the end of this report we are involved, under sponsorship from other agencies, in applying higher-order statistical signal processing to a variety of problems in science and engineering. In contrast to the application work supported by other agencies, in this specific JSEP project we are primarily concerned with applications to nonlinear distortion in, for example, communication systems, and nonlinear signature analysis.

Volterra series models have been widely used to model nonlinearities in devices that may result in distortion. It seems reasonable that before one can begin to compensate or mitigate against the effects of such nonlinearities one needs a suitable and accurate model. Since nonlinear distortion results in the flow of energy from signal spectral components to other, and possibly interfering, spectral components, the use of higher-statistical processing to determine the relevant Volterra kernels is a potentially powerful approach to characterize the nonlinear spectral flow of energy associated with such distortion. Furthermore, the use of higher-order statistical signal processing allows for the possibility of quantifying nonlinear distortion using broad-band random inputs, rather than multi-tone inputs the use of which may be both time consuming and tedious. Thus an important application objective is to explore the feasibility of utilizing random broad-band signals and higher-order statistical signal processing techniques to quantify the nonlinear distortion of both devices and systems. A second objective involves developing a program automating the distortion analysis and frequency assignment problem by utilizing new and improved algorithms for counting and sorting third-order intermodulation products.

There are several application areas where it is desirable to reduce the acoustic or electromagnetic energy either radiated (passive detection) or scattered (active detection) by an object. If, however, in reducing this emitted or scattered radiation, nonlinearities are inadvertently introduced, the possibility arises of detecting and classifying the emitting or scattering object in terms of the associated intermodulation or harmonic components in the scattered signal. In other words, the scattering object possesses a nonlinear signature which may be used to possibly detect and classify the scattering object. A particular advantage of using higher-order spectral analysis techniques is that detection of the nonlinear signature depends (to first order) not so much on the amplitude of the scattered intermodulation spectral components, but rather on the phase coherence existing between the intermodulation products in the scattered signal and their "parent" spectral components in the incident signal. Since higher-order spectral analysis is very sensitive to this multi-frequency phase coherence, these techniques open up the possibilty of detecting nonlinear signatures under relatively poor signal-to-noise ratio conditions.

Our objectives in considering nonlinear signatures associated with scattering from nonlinear objects include (i) characterization of the target in terms of a hierarchy of linear, quadratic, and cubic cross sections, (ii) determination of such cross sections by appropriate higher-order statistical signal processing of transmitted and received signals, and (iii) investigation of the ability of higher-order statistical signal processing techniques to detect nonlinear signatures under various signal-to-noise ratios.

B. PROGRESS: In the following we describe progress in utilizing higher-order statistical signal processing in nonlinear system identification and applications.

Nonlinear System Identification: There are a number of practical applications where it is important to have the capability to model dual-input nonlinear systems, some examples of which follow: ground vibration tests of aircraft where two random exciting forces are applied in order to inject sufficient energy into all modes of the system; and experimental studies of transistion to turbulence in fluids and plasmas, where the two "inputs" consist of two different velocity components, and plasma density and potential fluctuations, respectively. In ref. [1] we present a digital method of estimating, from the raw input and output time series data, the linear and quadratic frequency-domain Volterra kernels (transfer functions) necessary to characterize a quadratically nonlinear system with two inputs and multiple outputs. The transfer functions are expressed in terms of various higher-order spectra which, in turn, are estimated from the raw input and output time series data. The approach is valid for both nonGaussian and Gaussian random excitation. The concept of coherence spectra is generalized to quantify the overall goodness of the model and to quantify (in a normalized sense) the nonlinear transfer of energy from various spectral

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bands in the two inputs to other spectral bands in the output of a quadratically nonlinear system. Consideration of two inputs (compared to one input) greatly increases the computational complexity of estimation of all six relevant Volterra kernels of which two are linear and four quadratic. Fortunately, we find our algorithm is highly vectorizable, and thus runs very efficiently on a supercomputer.

In past reports we have indicated that we have extended our capability to determine frequency-domain Volterra kernels up to third-order (i.e., cubic systems). Although, the extension from quadratic to cubic systems is conceptually straightforward, the degree of complexity increases tremendously. There are two reasons for this. First, to describe the features of a cubically nonlinear system we must operate in a three-dimensional frequency space (as opposed to one-dimension for a linear system, and two-dimensions for a quadratic system). Second, for nonGaussian excitation the statistics of the excitation signal must be characterized up to sixth order (i.e., we must compute up to sixth-order spectral moments). These challenges have been overcome, and in ref [4] we summarize an approach, based on higher-order statistical signal processing, to determine linear, quadratic, and cubic frequency-domain Volterra kernels for both nonGaussian and Gaussian random excitation. This is a significant step forward, since in many systems of interest, the dominant nonlinearity is cubic rather than quadratic. Because the resulting model is valid for nonGaussian excitation, it is nonorthogonal. Thus, when the model is used to "predict" the power spectrum of the response of a nonlinear system, "interference" terms appear. These interference terms result from the interaction of the outputs the linear, quadratic, and cubic components of the model. The contribution of an interference term to the "predicted" response power spectrum can be either positive or negative, depending on the relative phases of the interfering terms. As a result it is often difficult, if not impossible, to meaningfully evaluate the relative linear, quadratic, and cubic contributions to the response power spectrum. For this reason in ref [9] we describe an orthogonalization scheme in the frequency domain, which is based upon ordered sets of conditioned orthogonal higher-order input vectors. The Gram-Schmidt method underlies the approach which is valid for both nonGaussian and Gaussian random excitation. A new set of Volterra transfer functions for the conditioned orthogonal Volterra system is obtained from a coordinate transformation of a Volterra system based upon non-orthogonal higher-order input vectors. The orthogonal model has the same minimum mean square error as the original model of ref [4] but without the "interference" terms. This lack of interference greatly facilitates meaningful interpretation of the nonlinear system as is exemplified in [12].

Our work on estimating first, second, and third-order Volterra kernels has led to an efficient approach for the selective counting of third order products associated with distortion resulting from cubic nonlinearities [5].

As indicated above the determination of the frequency domain Volterra kernels of a cubically nonlinear system when excited by nonGaussian excitation is a relatively complex process. On the other hand, we have considered other excitations such as i.i.d. (independent, identically distributed) which appear to be a relevant class of signals in digital communications. In refs. [3] and [10] we exploit the properties of i.i.d. signals to greatly simplify the determination of Volterra kernels for both quadratically and cubically nonlinear systems, respectively. The algorithms based on i.i.d. inputs does not require estimation of higher-order moments up to sixth-order nor does it require the calculation of the inverse of an "input" matrix, which in the general case contains various moments of the input up to fourth-order for quadratic systems and sixth-order for cubic systems. The i.i.d. algorithms have been written, and digitally implemented. Tests have demonstrated that the reduction in complexity is truly significant.

Applications: In refs. [2] and [8] a digital spectral method to evaluate second-order distortion of a nonlinear system, which can be represented by Volterra kernels up to second order and which is subjected to a random noise input, is discussed. The importance of departures from the commonly assumed Gaussian excitation is investigated. Tests for Gaussianity of two important sources, which are commonly used for Gaussian inputs in nonlinear system identification are presented: 1) commercial software routines for simulation experiments and 2) noise generators for practical experiments. The deleterious effects and misleading results of assuming a Gaussian input when, in fact, it is not, are demonstrated. The random input method to evaluate (in terms of the second-order Volterra kernels and

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distortion factors) the second-order distortion of a nonlinear system is compared with the sine-wave input method using both simulation and experimental data. Furthermore, good agreement is achieved between estimators of intermodulation distortion based on the random-input Volterra approach and the more classical approach of measuring intermodulation distortion using tones. The proposed approach is utilized to model, identify, and quantify the linear response and second-order distortion products by using higher order coherence spectra.

Our previous work on characterizing the nonlinear scattering features of a target in terms of linear, quadratic, and cubic scattering cross sections suffered from one serious practical limitation, namely, it was restricted to incident signals exhibiting Gaussian statistics. Eliminating the Gaussian assumption generally results in non-orthogonal models, which means that one must also account for the contributions of the "interference" terms (discussed previously) to the scattered power received at the receiver. One possible way to handle this would be to include hybrid scattering cross sections (such as linear-quadratic, linear-cubic, and quadratic-cubic) to account for the interference contributions to the total scattered power. This is a cumbersome approach at best since the required number of cross-sections to describe a cubic target would be six, the linear, quadratic, and cubic cross-sections plus the three hybrid cross-sections mentioned above. Our current work involves utilizing our new orthogonal model to characterize a cubically nonlinear scattering object. This approach offers two advantages: (1) it is valid for both nonGaussian as well as Gaussian incident signals, and (2) the nonlinear features of the scattering object can be characterized by a hierarchy of just three scattering cross sections (linear, quadratic, and cubic).

Technology Transfer: Higher-order statistical signal processing and nonlinear system identification based on it offer excellent technology transfer potential. For example, these advances have been used to quantify the nonlinear response of ships [12] (sponsored by ONR) and offshore structures[11] (sponsored by NSF) to nonGaussian random seas, and to quantify the role of nonlinear wave interactions underlying transistion to turbulence [7] (sponsored by the Texas Advanced Research Technology Program).

C.   FOLLOW-UP STATEMENT: This work will continue with particular emphasis on relaxing the computational complexity and the amount of raw data that must be collected to estimate the kernels of a third-order Volterra system.

I.   LIST OF PUBLICATIONS

Journal Articles (supported entirely or in part by JSEP, *denotes a publication primarily supported by another grant(s)/contract(s) in which JSEP is acknowledged for nonlinear signal processing contribution).

1.   C.K. An, E.J. Powers, and C.P. Ritz, "A Digital Method of Modeling Two-Input Quadratic Systems with General Random Inputs," IEEE Trans. on Signal Processing, Vol. 39, No. 10, pp. 2320-2323, October 1991.

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3.   Y.S. Cho and E.J. Powers, "Quadratic System Identification Using Higher-Order Spectra of I.I.D. Signals, accepted for publication in IEEE Transactions on Signal Processing

4.   S.W. Nam and E.J. Powers, "Application of Higher-Order Spectral Analysis to Nonlinear System Identification," submitted for publication.

5.   S.W. Nam and E.J. Powers, "On the Selective Counting of Third-Order Products," submitted for publication.

6. *S.K. Kniffen, M.F. Becker, and E.J. Powers, "Bispectral Magnitude and Phase Recovery Using a Widebandwidth Acousto-optic Processor," Applied Optics, Vol. 31, No. 8, pp. 1015-1029, March 10, 1992.

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II. LIST OF CONFERENCE PROCEEDINGS

Conference Proceedings (supported entirely or in part by JSEP, *denotes a publication primarily supported by another grant(s)/contract(s) in which JSEP is acknowledged for nonlinear signal processing contribution).

8. Y.S. Cho and E.J. Powers, "Two-Tone vs Random Process Inputs for Nonlinear Distortion Estimation," Proceedings of the 1992 IEEE International Conference on Acoustics, Speech, and Signal Processing, Vol. II, pp. II209-212, San Francisco, California, March 23-26, 1992.

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II. LIST OF THESES AND DISSERTATIONS

Ph.D.

W.T. Oh, "Application of Higher-Order Statistics to Time Delay Estimation for Passive Sonar Systems," May 1992.

III. CONTRACTS AND GRANTS

E.J. Powers and R.W. Miksad, "Applications of Higher-Order Statistics to Nonlinear Seakeeping," Office of Naval Research, October 1, 1991 to September 30, 1994.

E.J. Powers, "Quantification of Fluid-Structure Interactions," a project supported by the Offshore Technology Research Center, an NSF Engineering Research Center, (NSF Grant CDR-8721512) at both The University of Texas at Austin and Texas A&M University.

R.O. Stearman and E.J. Powers, "Aeroelastic System Identification of Advanced Technology Aircraft Through Higher Order Signal Processing," Texas Advanced Technology Program, Grant No. 003658-224, Jan. 1, 1990 - August 31, 1992.

E.J. Powers and R. W. Miksad, "Nonlinear System Identification of Tension Leg Platform Dynamics," Texas Advanced Technology Program, Grant No. 003658-392, Jan. 1, 1990 - August 31, 1992.

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